Magnetic fields & cosmic rays in galaxy formation

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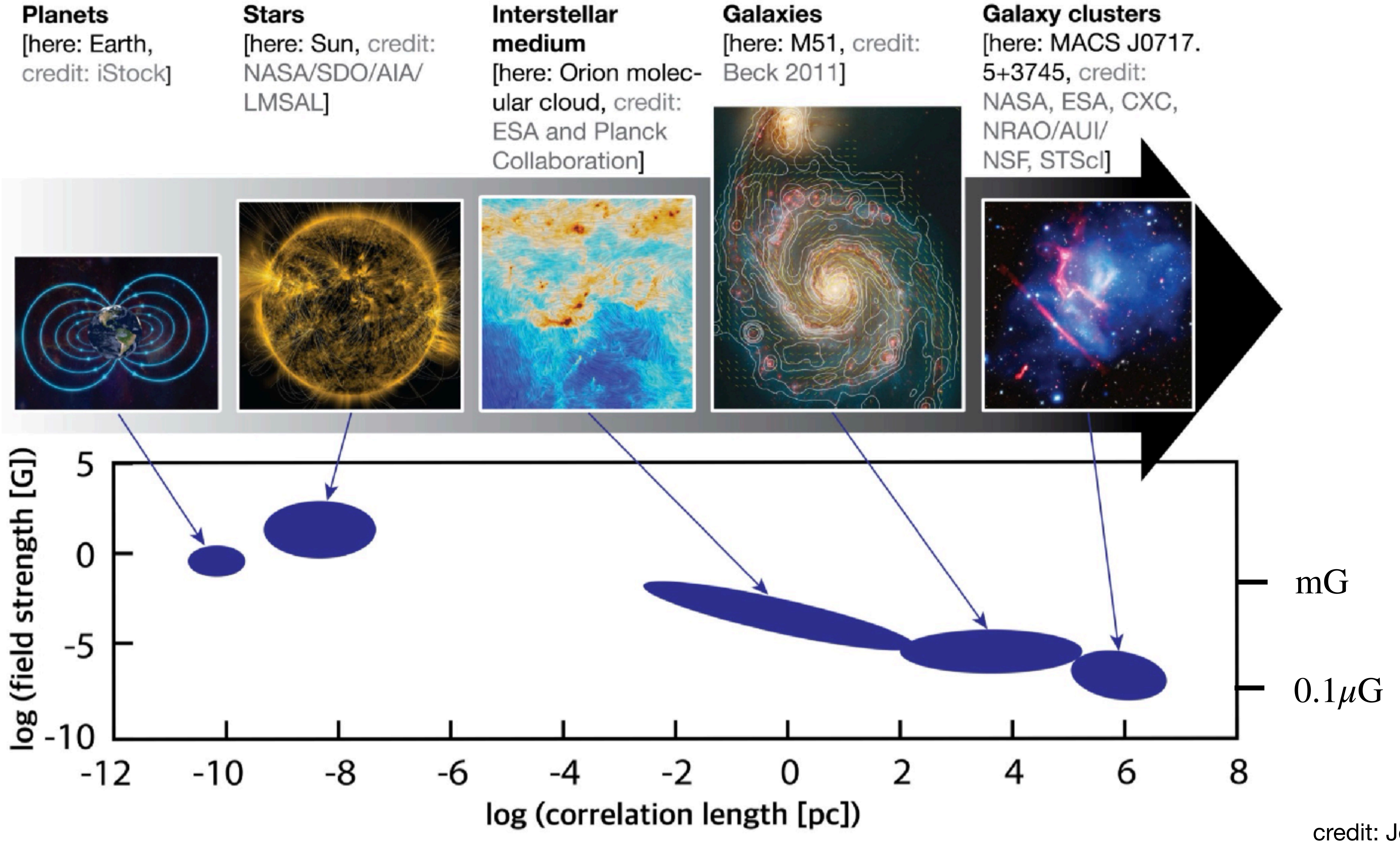
Magnetic fields everywhere



credit: Jennifer Schober

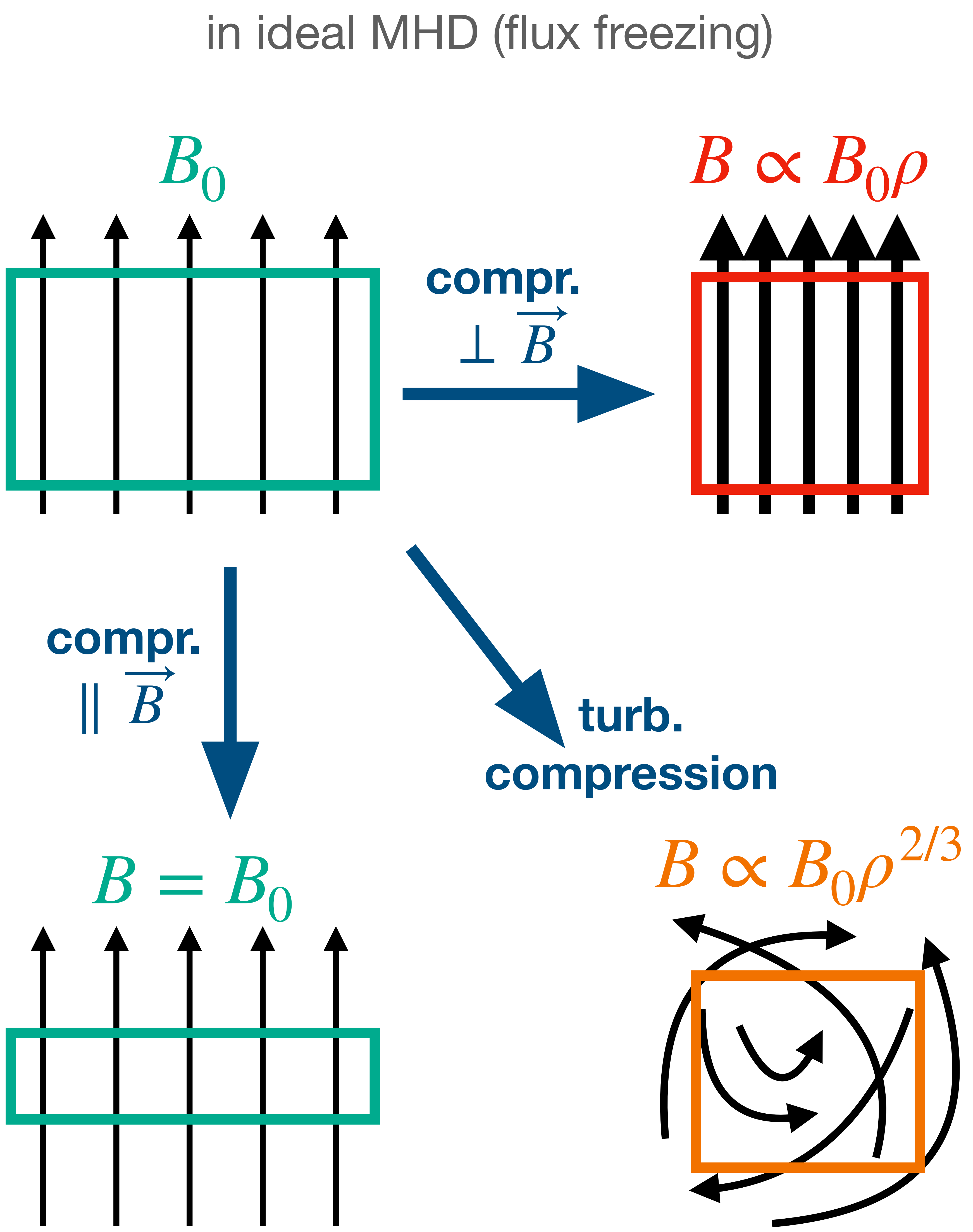
Astrophysical magnetic fields

- Biermann battery (Biermann 1950)
  interactions of $e^- + \gamma_{\mathrm{CMB}}$ (Mishustin & Ruzmaikin 1972):
  $\Rightarrow$ seed field $B_{\mathrm{seed}} \sim 10^{-20}\,\mathrm{G}$

- B_{seed} + flux freezing + compression
  $\Rightarrow B_{\mathrm{seed}} \dfrac{\rho}{\rho_0} \sim 10^6 B_{\mathrm{seed}} \sim 10^{-14}\mathrm{G}$: too weak!

- need a dynamically amplified field

- $\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta\, \nabla^2 \mathbf{B}$



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  interactions of $e^- + \gamma_{\rm CMB}$ (Mishustin & Ruzmaikin 1972):
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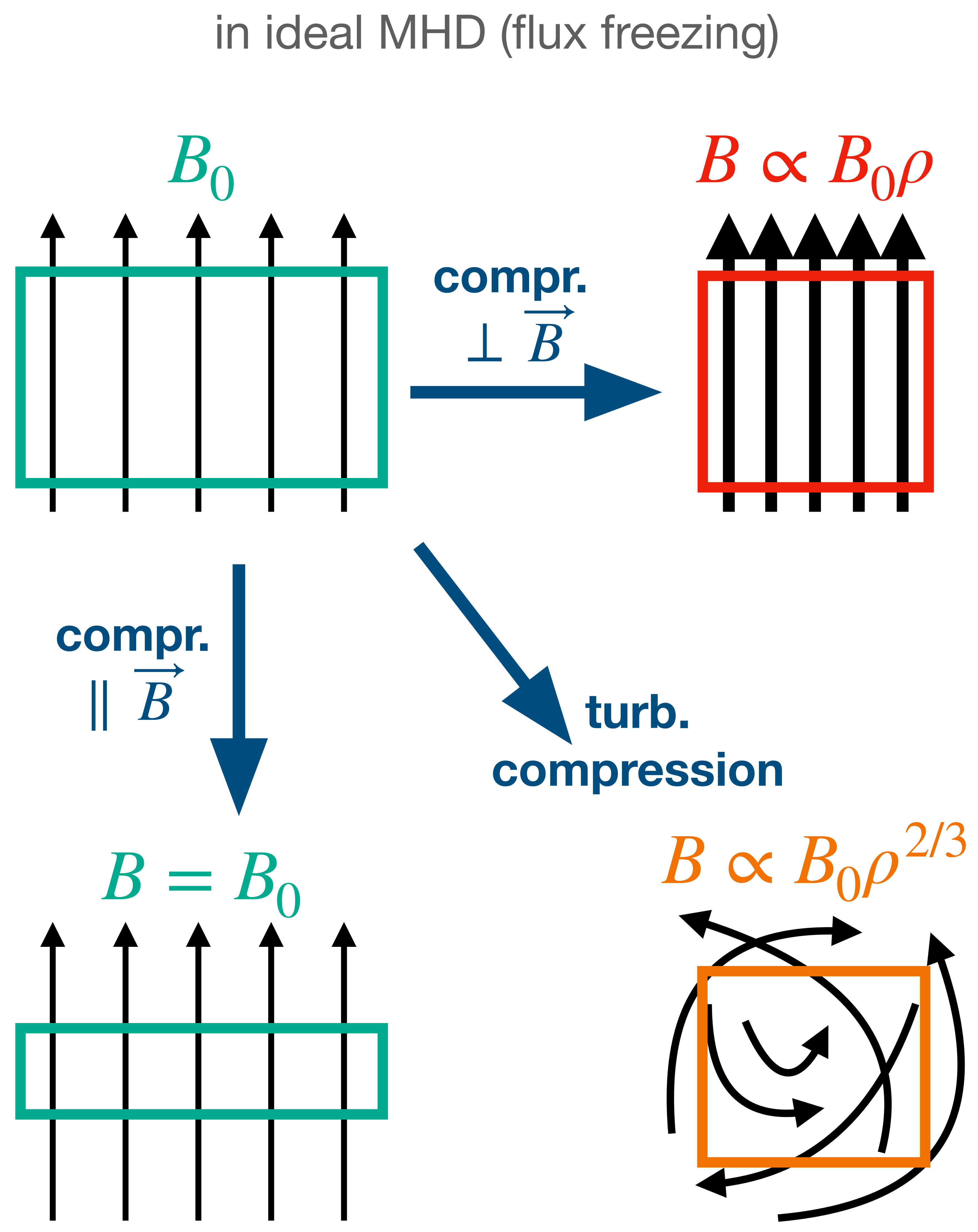
- $\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$

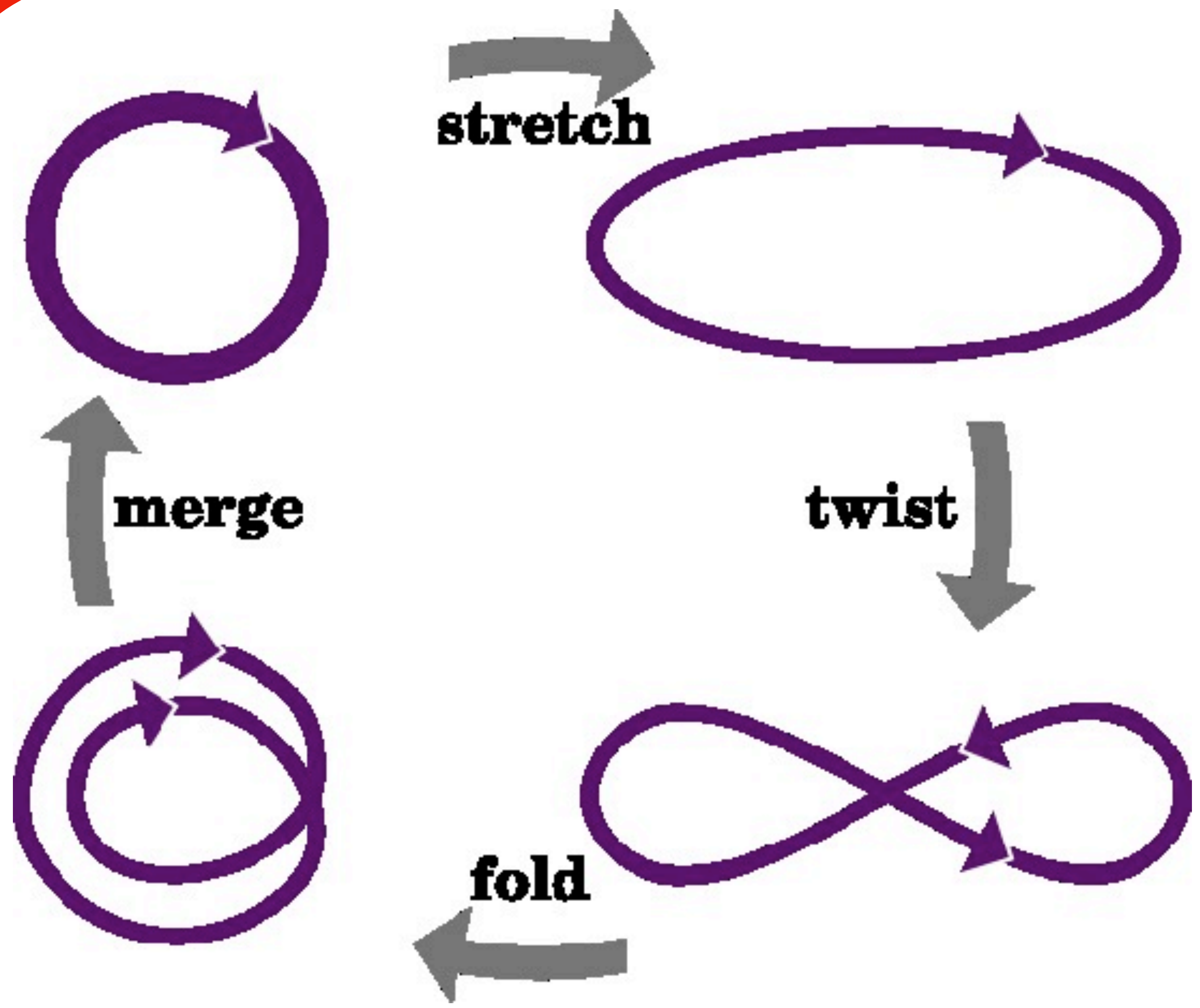
- ideal MHD (ionisation > 10^{-6})
  no free parameters, theory "fully" understood



Magnetic field strength

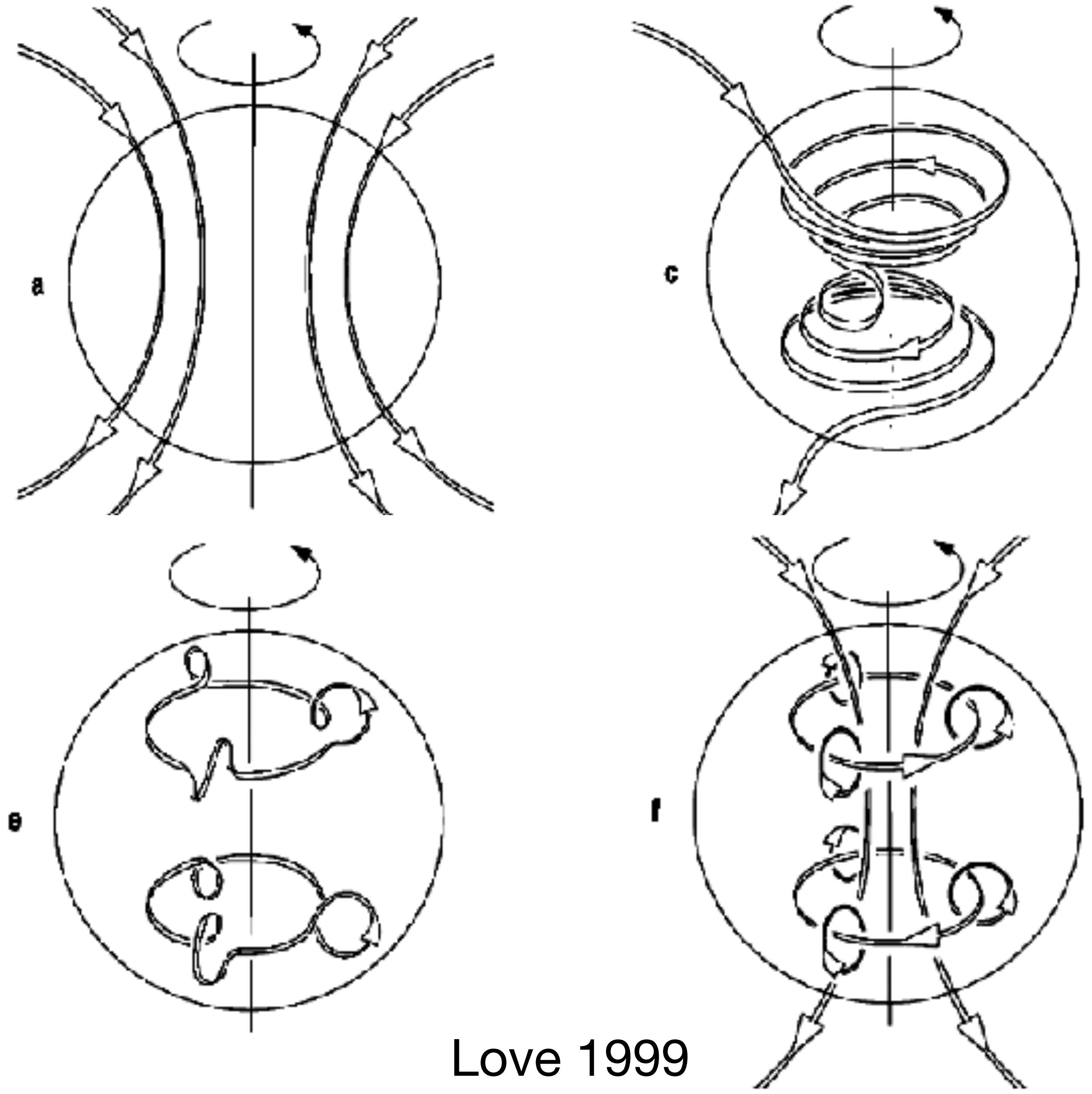
- dynamo: convert $E_{\rm kin} \rightarrow E_{\rm mag}$
- saturation $E_{\rm mag} \approx 0.1 - 0.3\, E_{\rm kin}$
- difficulty of understanding B:
  provide sufficient/relevant conditions
  (high Re_m, high Re)

small scale dynamo (fast)



Jennifer Schober

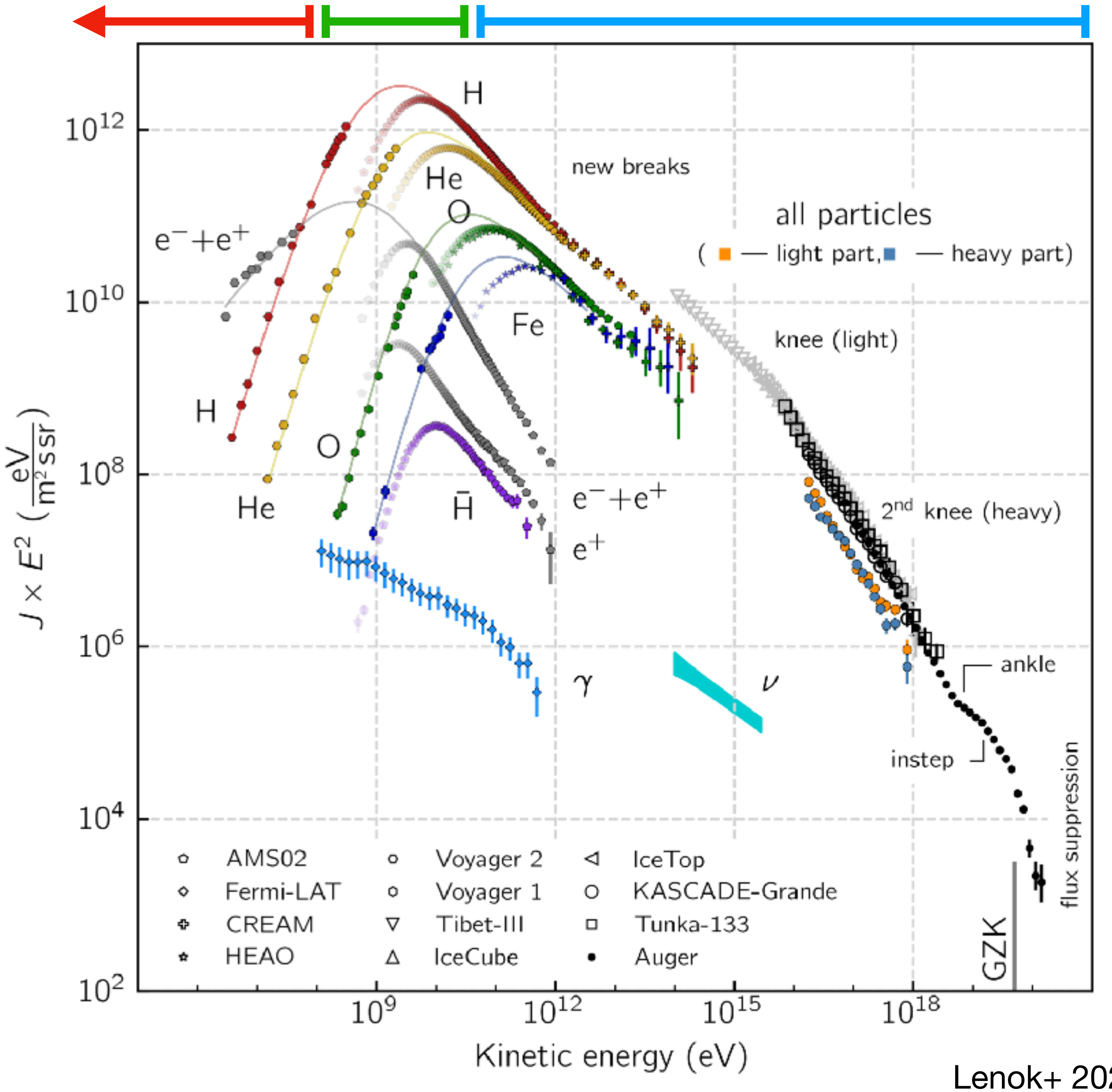
galactic α-Ω dynamo (slow)



Love 1999

Cosmic rays facts

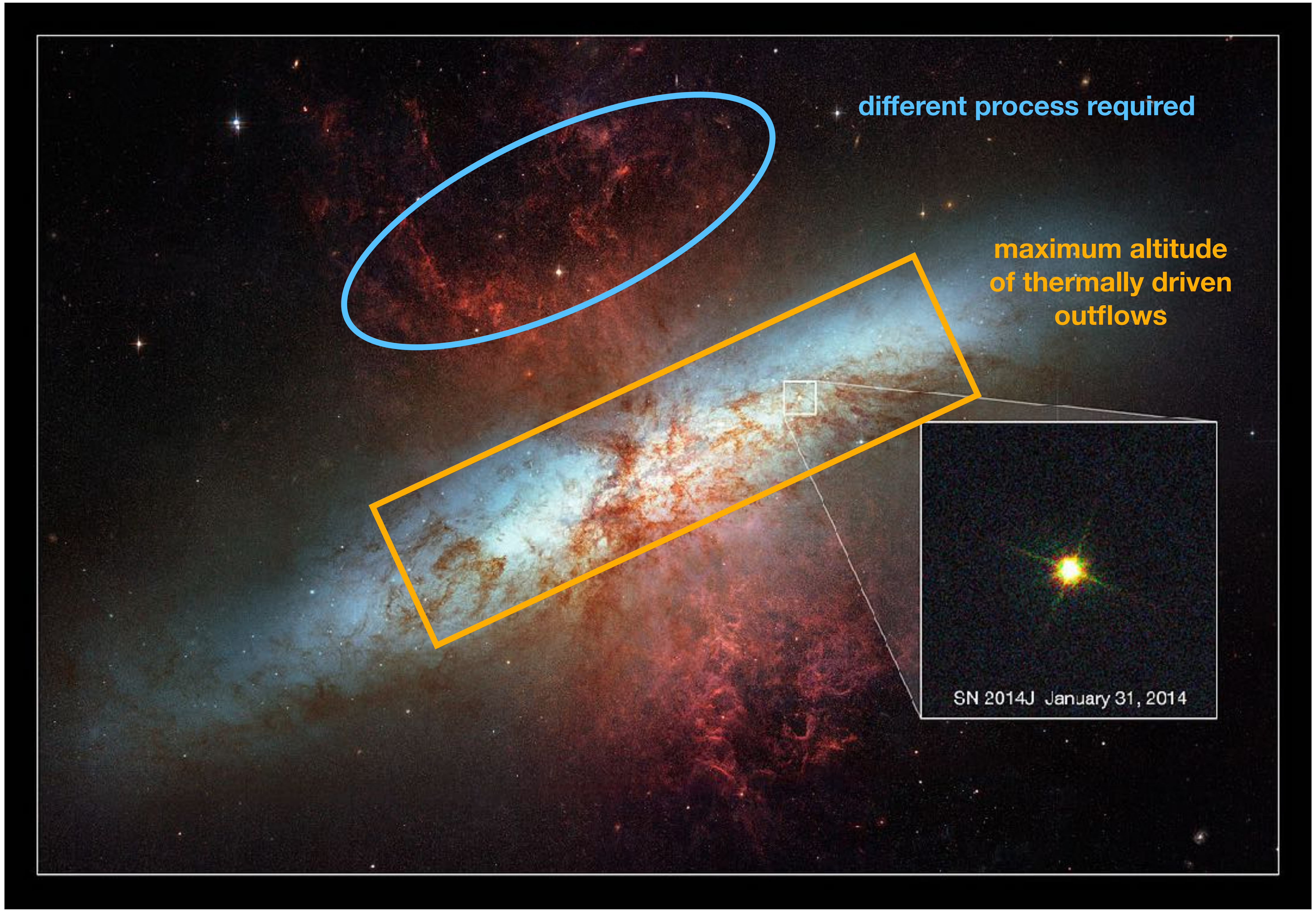
- 1912: discovery by Victor Hess (balloon experiment)
- no rays, but high energy particles $(p, e^+, e^-, \alpha \ldots)$
- **low-E CRs** (Padovani+2020)
  Large cross section with gas
  Strong losses
  heating of dense star forming regions
- **GeV CRs** (Ferriere 2001, Ruszkowsky & Pfrommer 2023)
  Most of energy (weak losses)
  Dynamically relevant via pressure:
  similar E-densities: $e_{\rm cr} \sim e_{\rm kin} \sim e_{\rm therm} \sim e_{\rm mag}$
- **high-E CRs** (Kotera&Olinto 2011)
  Low integrated energy
  Extragalactic
  important as **observational diagnostics**



Lenok+ 2022

Motivation for CRs in galaxies

classical stellar feedback too weak

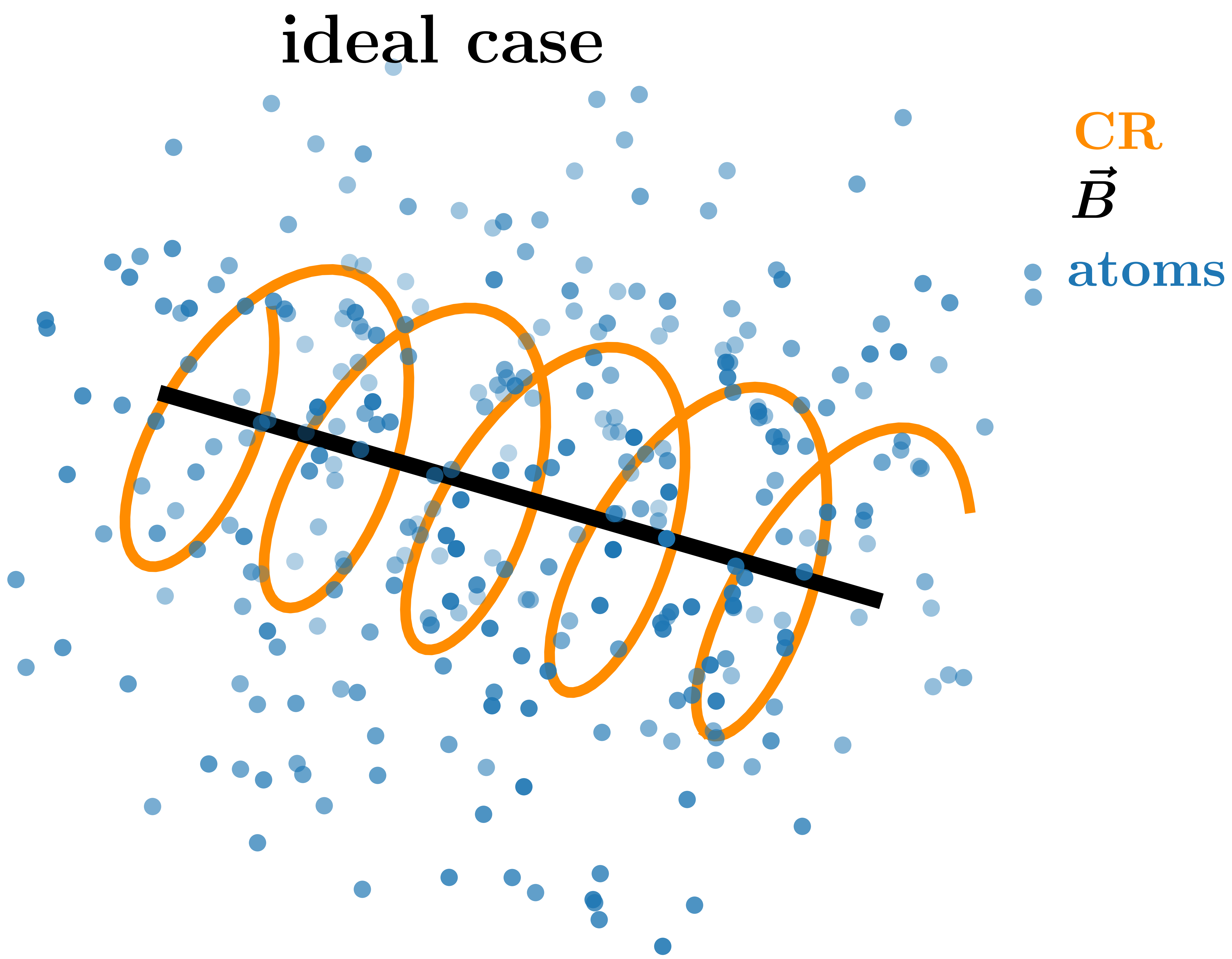


- evidence for strong outflows
- in all phases, H^+, H, H_2
- classical stellar feedback
  - cools too fast (SNe)
  - does not couple enough (γ)
  - too weak
    (winds, protost. outflows)

CR Transport illustrated

Advection

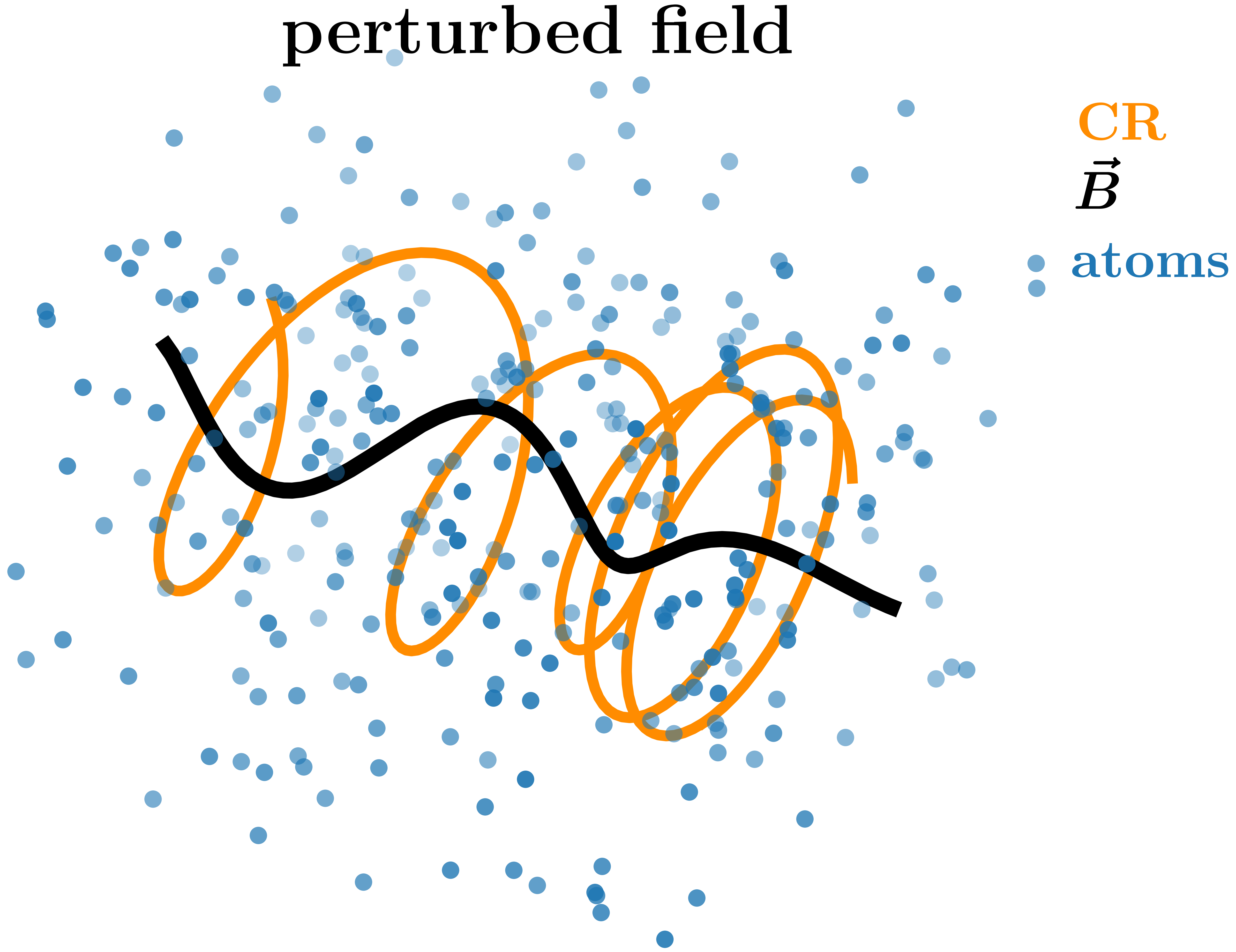
- CR gyrate around B
- vertical motions of B
  $\Rightarrow$ coupled to motions of CRs
- gas (partially) ionized
- ideal MHD, B frozen in gas
- CR $\Leftrightarrow$ B $\Leftrightarrow$ gas
- advection with the gas



CR Transport illustrated

Diffusion

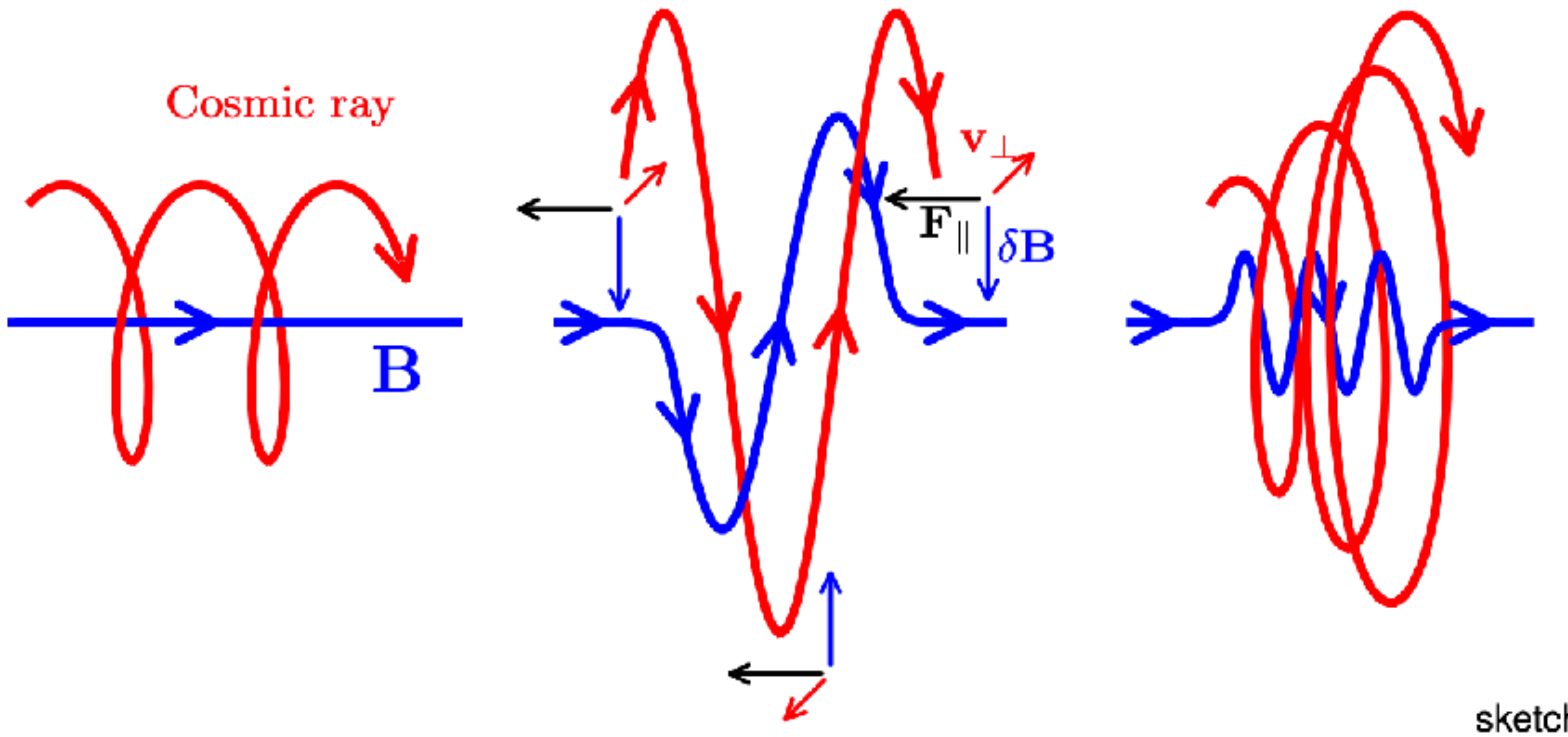
- perturbed field
- scattering off of B irregularities
- elastic scattering ⇒ diffusion
- realistic environment:
  turbulent 3D
- diffusion relative to the gas
- diffusion mainly along B



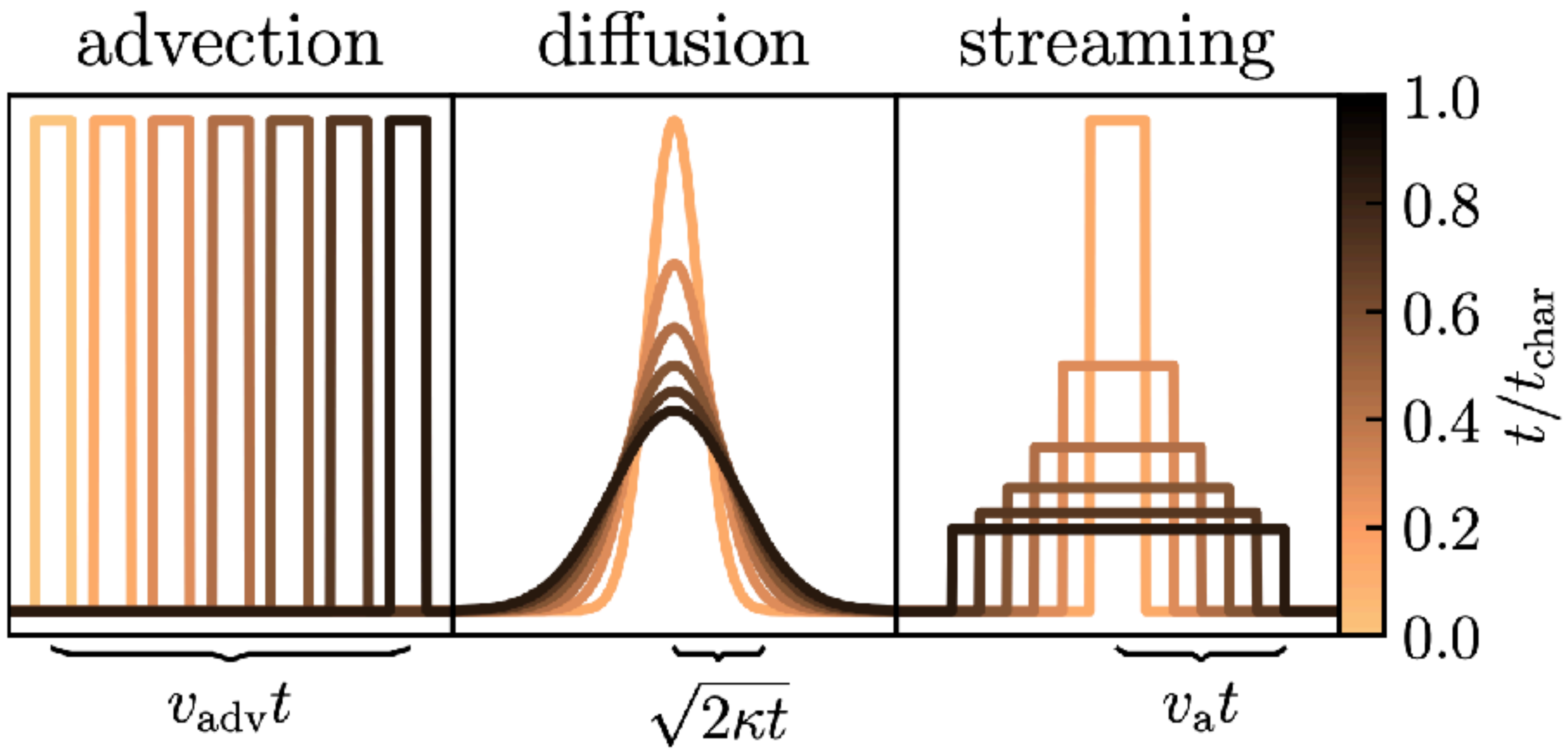
Back reaction CR $\Leftrightarrow B$

Streaming instability (Skilling 1975)

- back-reaction onto B-field, gyro-resonances
  $\Rightarrow$ no simple diffusion
  $\Rightarrow$ transport + E-transfer $E_{\rm cr} \leftrightarrow E_{\rm mag}$
- bulk of CRs streams with Alfvén speed, Alfvén heating
- equate growth and damping (Wiener+ 2013)
  $\Gamma_{\rm growth} = \Gamma_{\rm NLLD} + \Gamma_{\rm in} \;\Rightarrow H = -\mathbf{v}_{\rm A} \cdot \nabla P_{\rm cr}$
- new self-consistent PIC models (Shalaby et al. 2021/2023)
  $\Rightarrow$ many unknowns concerning
  - transport speeds
  - energy exchange



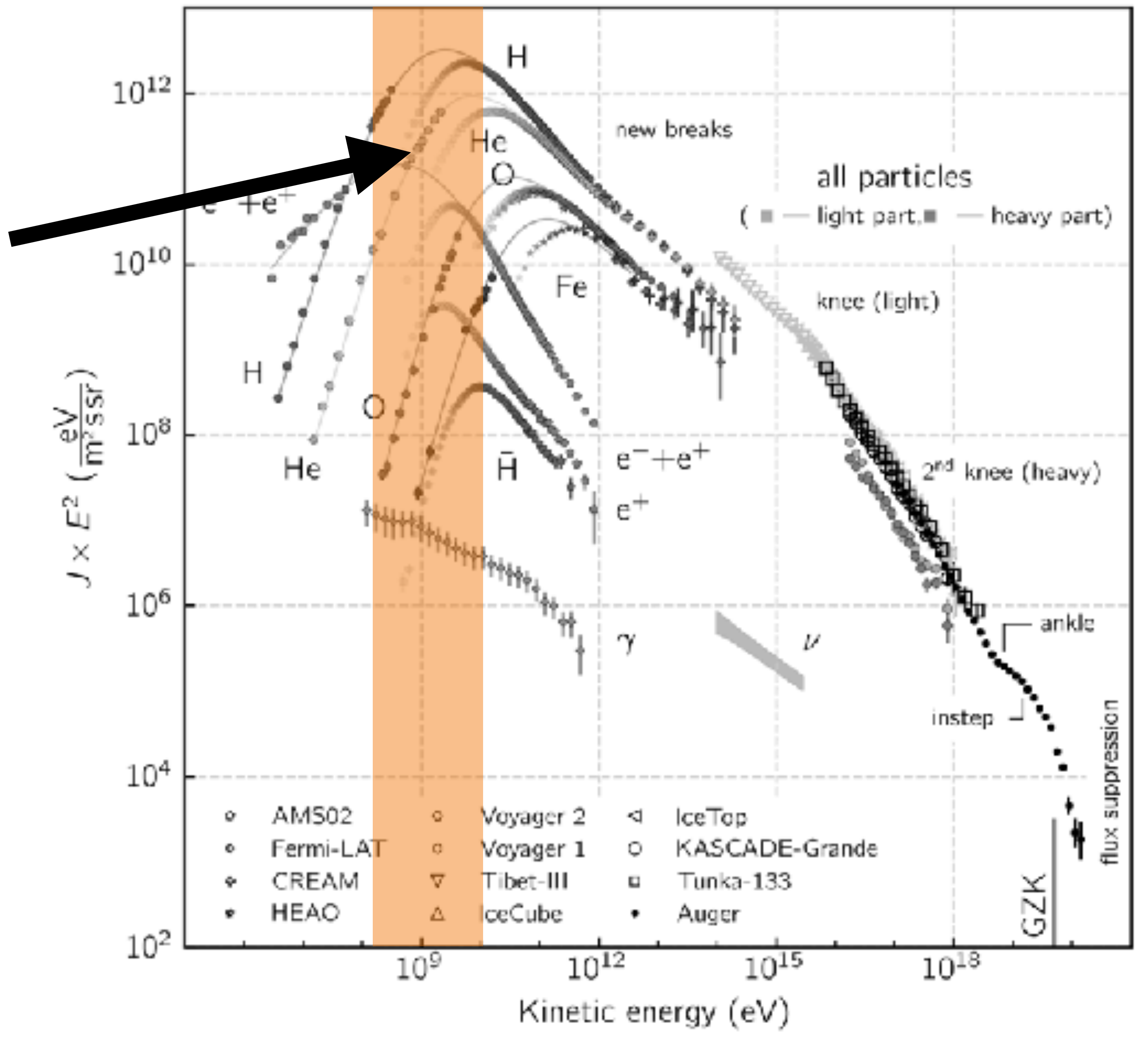
sketch: Jacob



Thomas, CP, Enßlin (2020)

CR+MHD (in grey approximation)

only integrated energy



$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) + \nabla p_{\rm tot} = \rho \mathbf{g}$$

$$\frac{\partial e_{\rm tot}}{\partial t} + \nabla \cdot \left[\left(e_{\rm tot} + p_{\rm tot} \right) \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g} - \nabla F_{\rm st} + \nabla \cdot \left(\mathsf{K} \cdot \nabla e_{\rm cr} \right) + Q_{\rm cr}$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0$$

advection $\quad \dfrac{\partial e_{\rm cr}}{\partial t} + \nabla \cdot \left(e_{\rm cr} \mathbf{v} \right) = -p_{\rm cr} \nabla \cdot \mathbf{v}$ adiabatic

$- \nabla F_{\rm st} - \Lambda_{\rm cr}$ streaming

$+ \nabla \cdot \left(\mathsf{K} \cdot \nabla e_{\rm cr} \right)$ diffusion

$+ Q_{\rm cr}$ sources/sinks

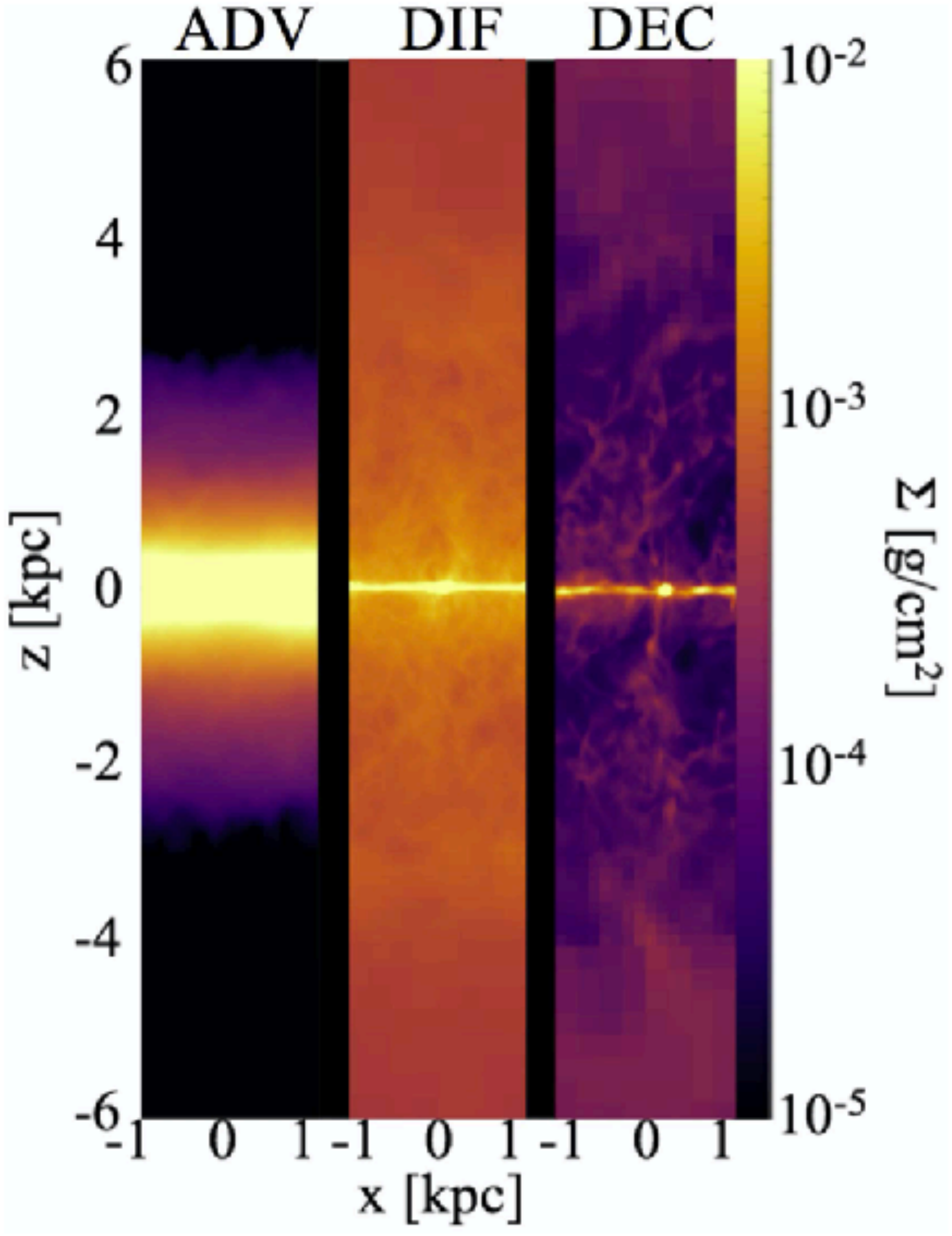
$$p_{\rm tot} = p_{\rm therm} + p_{\rm mag} + p_{\rm cr}$$

Piernik: Hanasz+2003
FLASH: Girichidis+2014,2016a
Arepo: Pfrommer+2017, Pakmor+2016,2017, Thomas+2021
RAMSES: Dubois+2016, Commercon+2019

review on numerics: Hanasz+ 2021

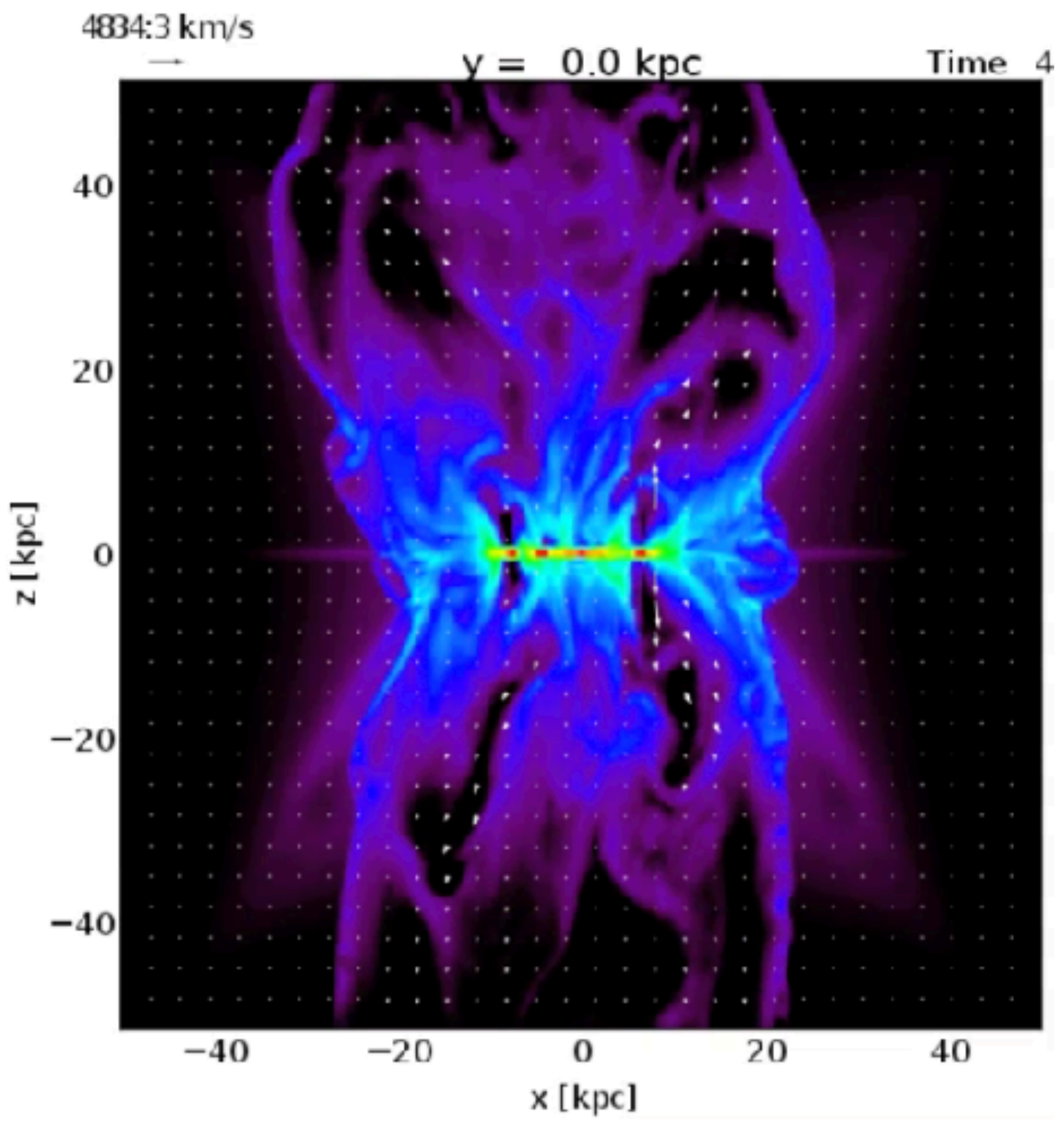
different setups

stratified boxes (ISM)



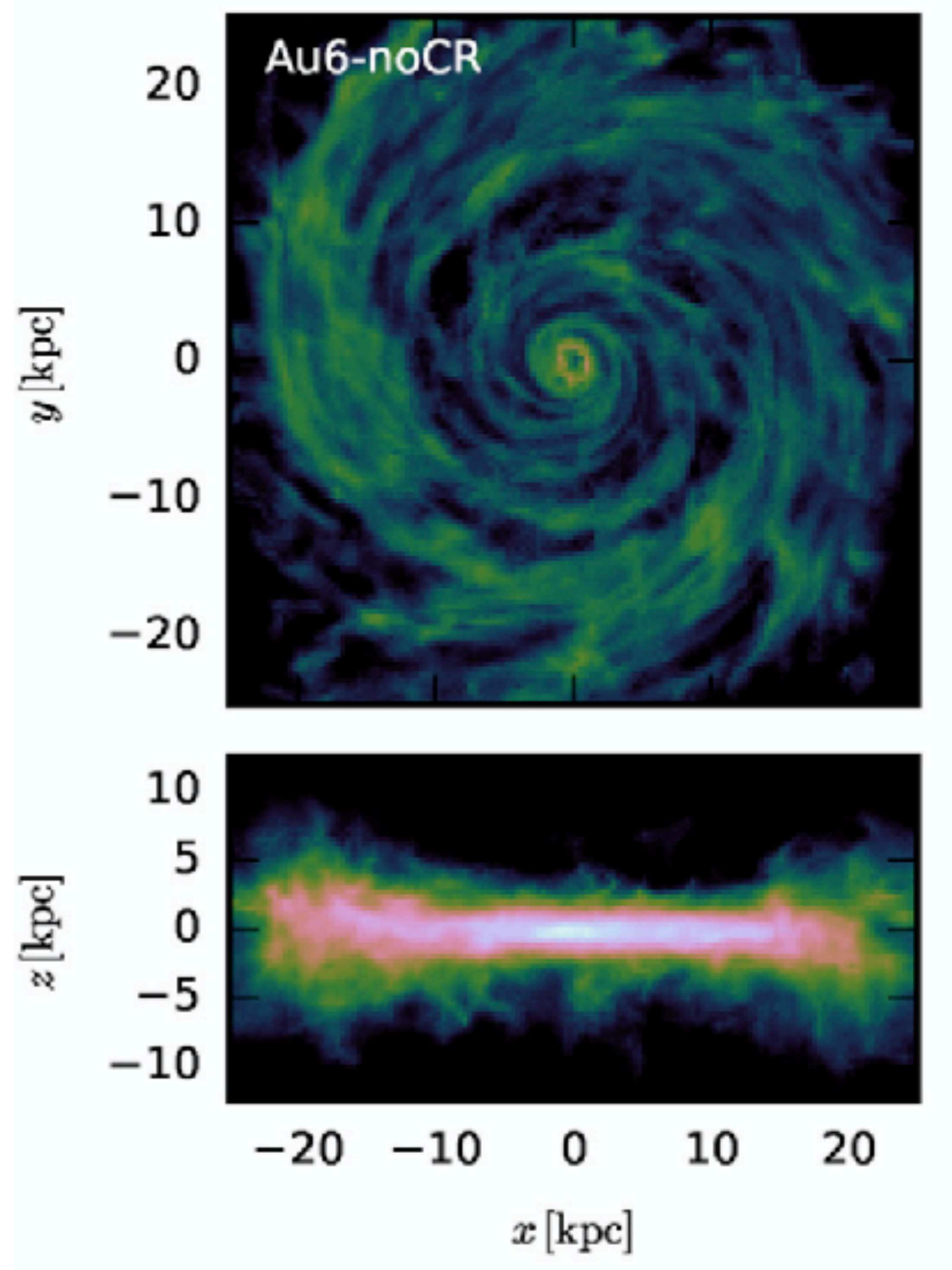
Hanasz+ 2003, Girichidis+ 2016,2018, Simpson+ 2016, Dubois+ 2016, Farber+ 2018, Armillotta+ 18,21,23 Commercon+ 2019, Butsky+ 2020, Rathjen+ 2021,2022

isolated galaxies



Booth+ 2013, Ruszkowski+ 2017a, Pakmor+ 2016, Pfrommer+ 2017, Jacob+ 2018, Dashyan+ 2020, Semenov+ 2021, Girichidis+ 2022/23, Thomas+ 2021,2023, Farcy+ 2022, Nunez-Castineyra+ 2022, Peschken+ 2023

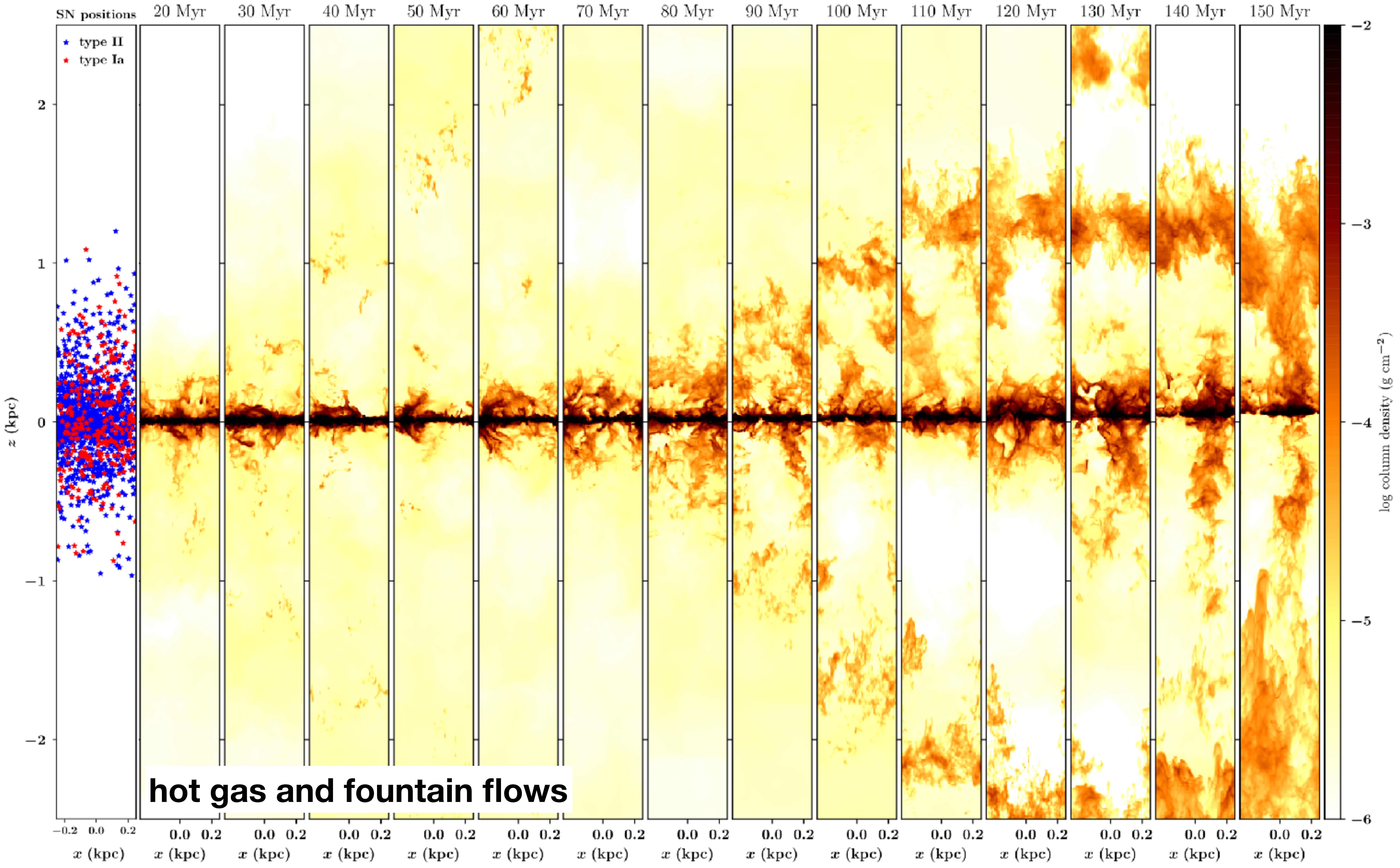
cosmological galaxies



Jubelgas+ 2008, Salem+ 2014, Chan+ 2018, Hopkins+ 2020/2021, Buck+2020, Ji+2020, Böss+ 2023, Rodriguez Montero+ 2023

ISM evolution without CRs

Girichidis et al. 2018a, based on SILCC setup (Walch+ 2015, Girichidis+2016)



ISM evolution (therm+CRs)

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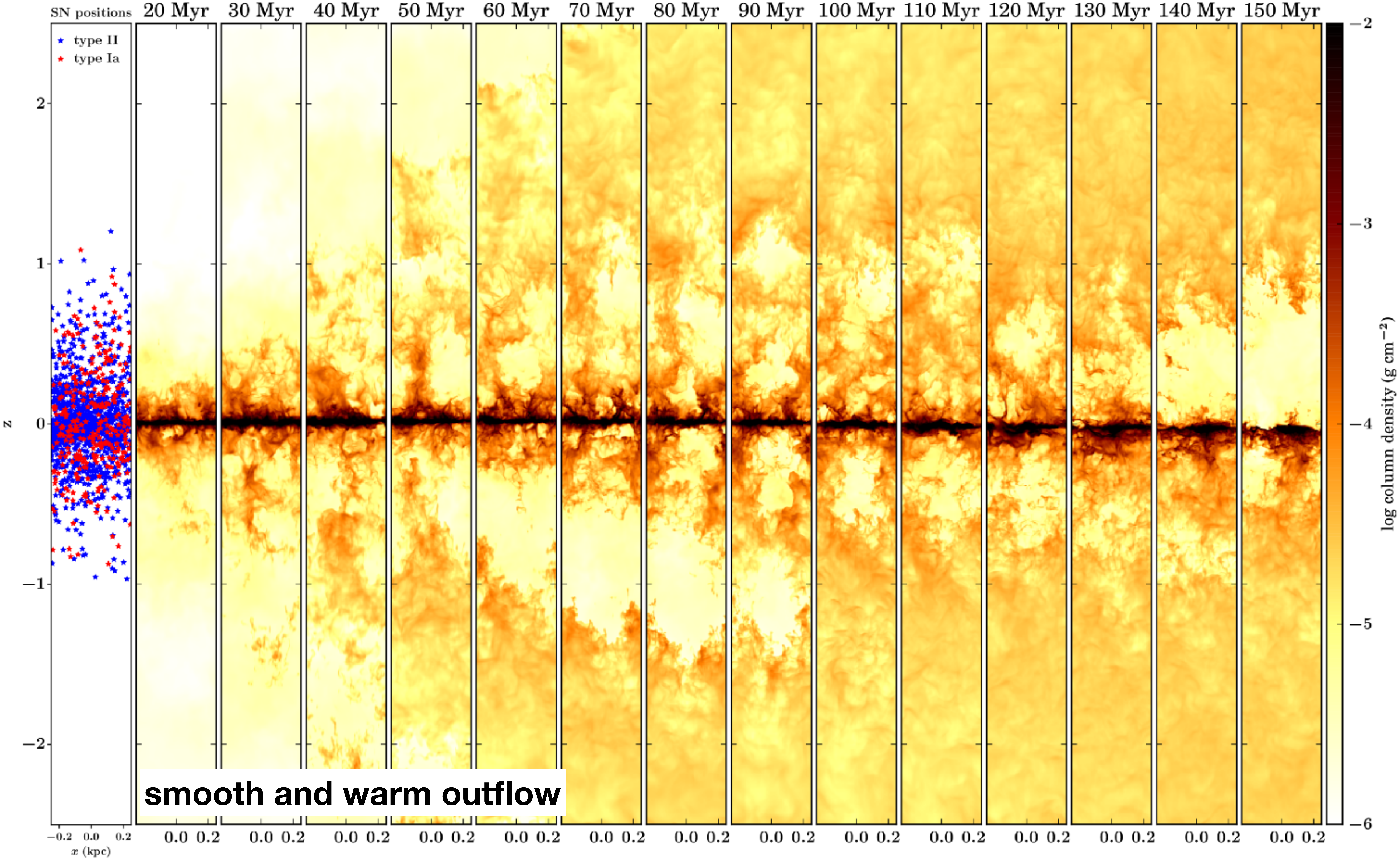

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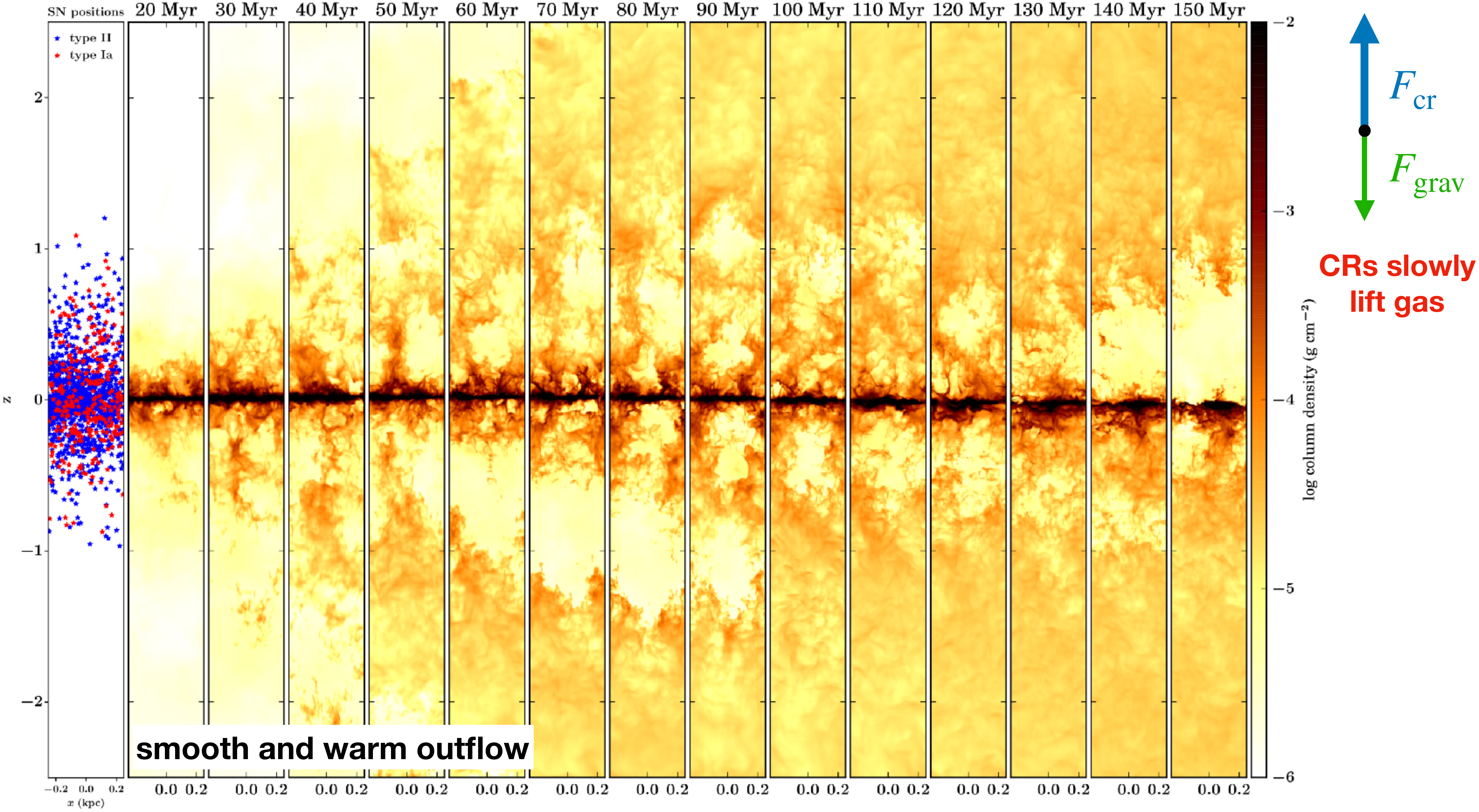


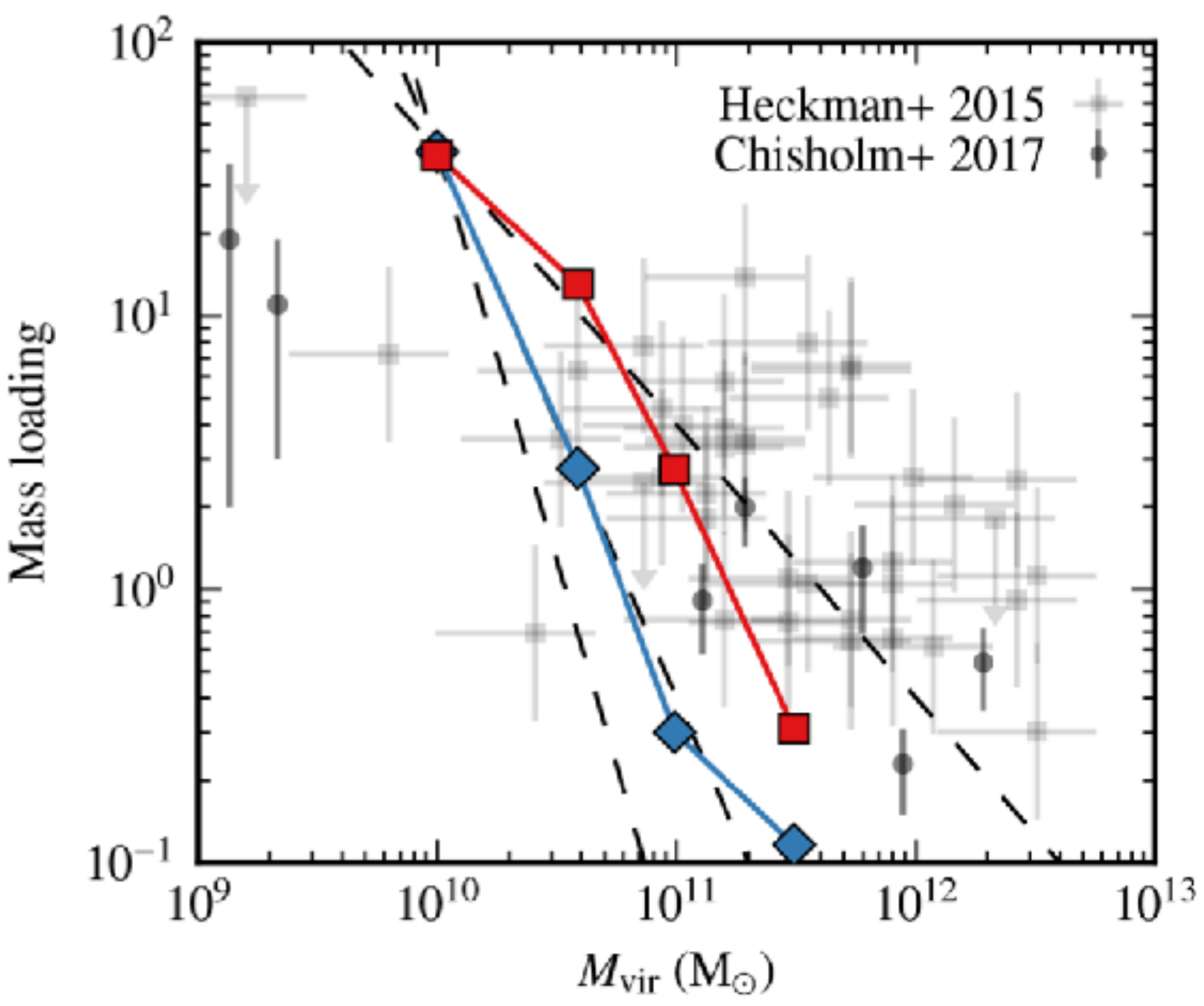
CRs slowly lift gas

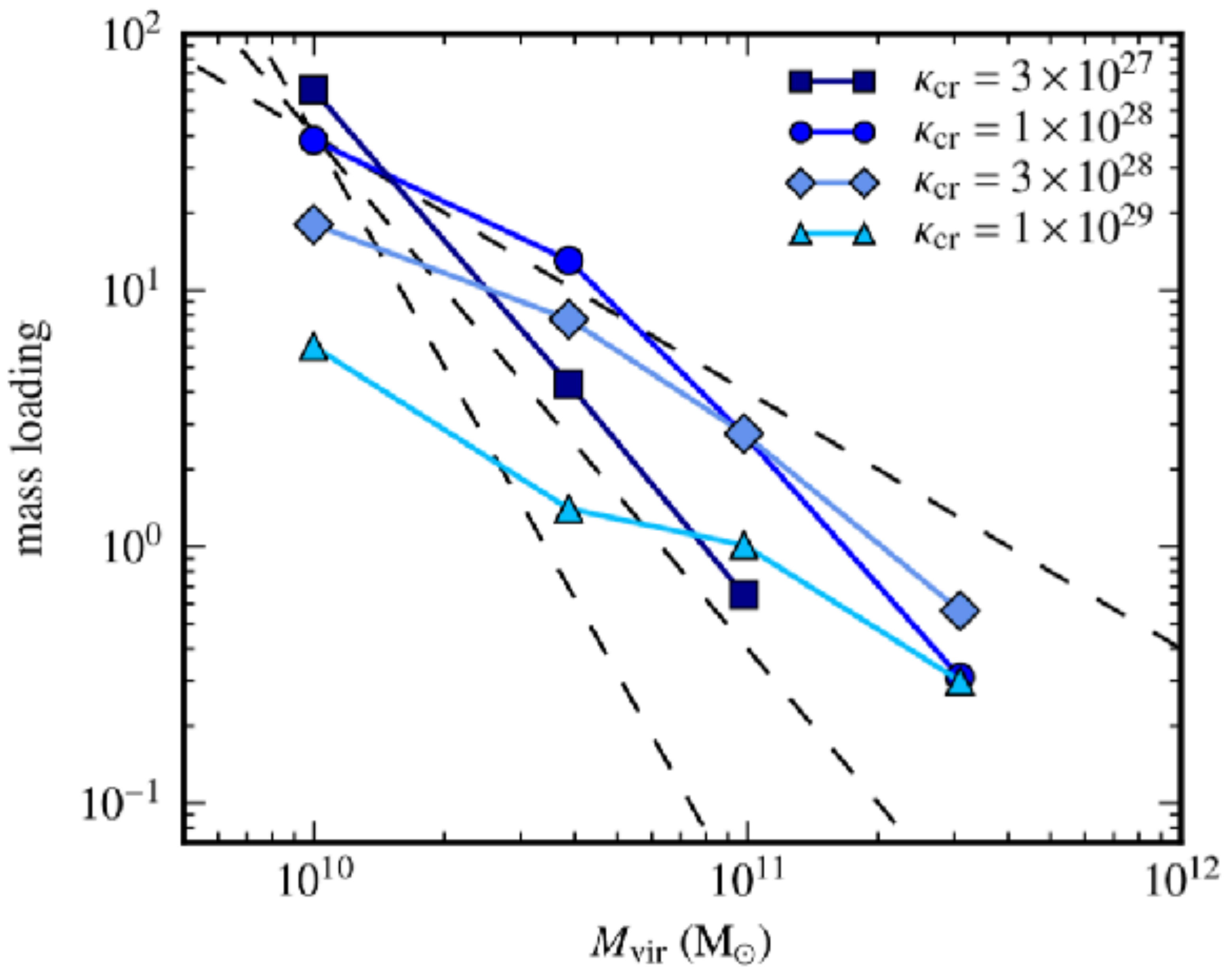
Halo mass dependence

- CR power for outflows is limited
- above $M \sim 3 \times 10^{11}\,\mathrm{M}_\odot$ no outflows
- depends on injection efficiency
- high diffusivity, weaker mass loading

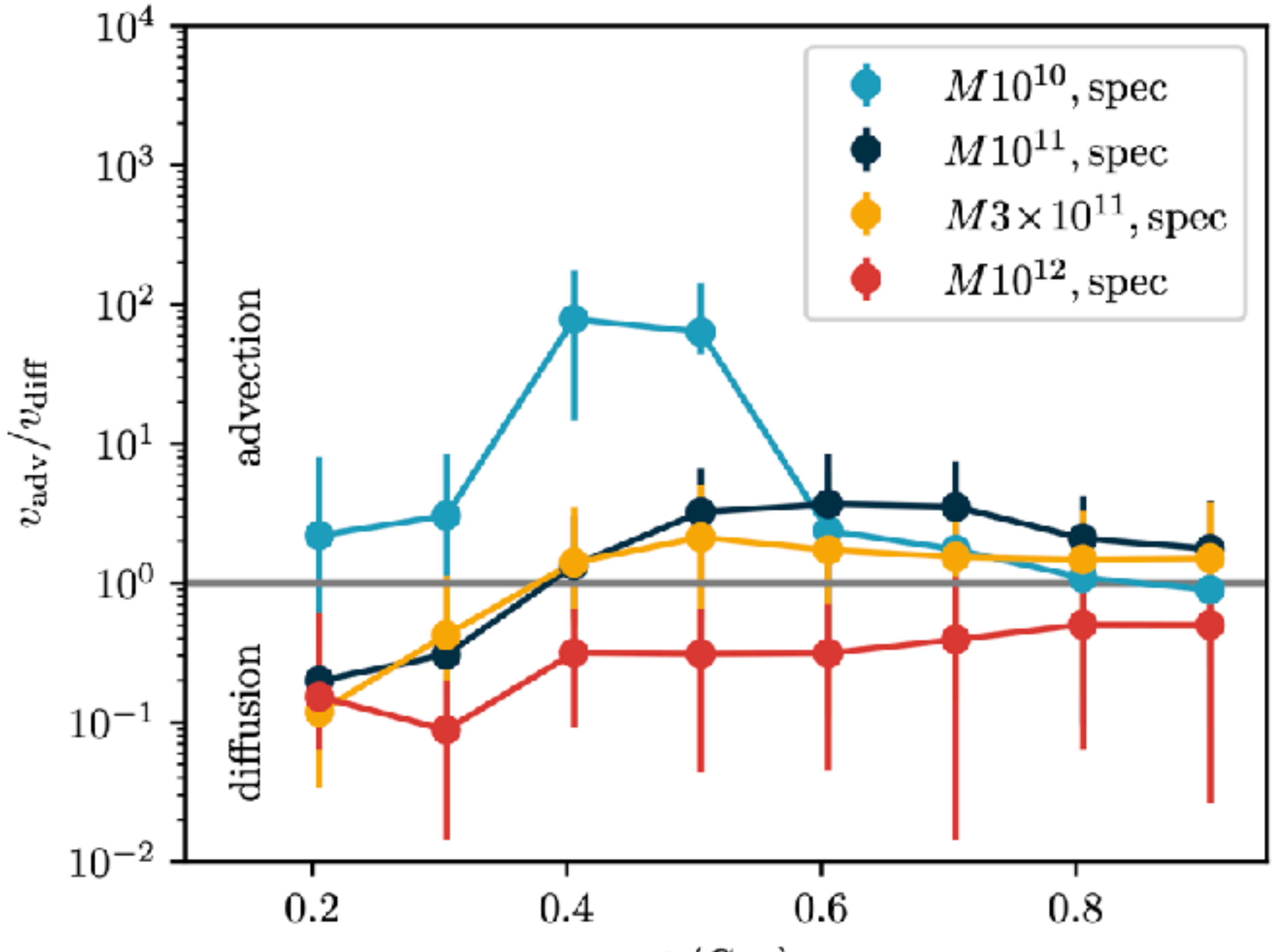
- in dwarf:
  CR transport mainly advective

- in MW:
  CR transport mainly diffusive





Jacob et al. 2018

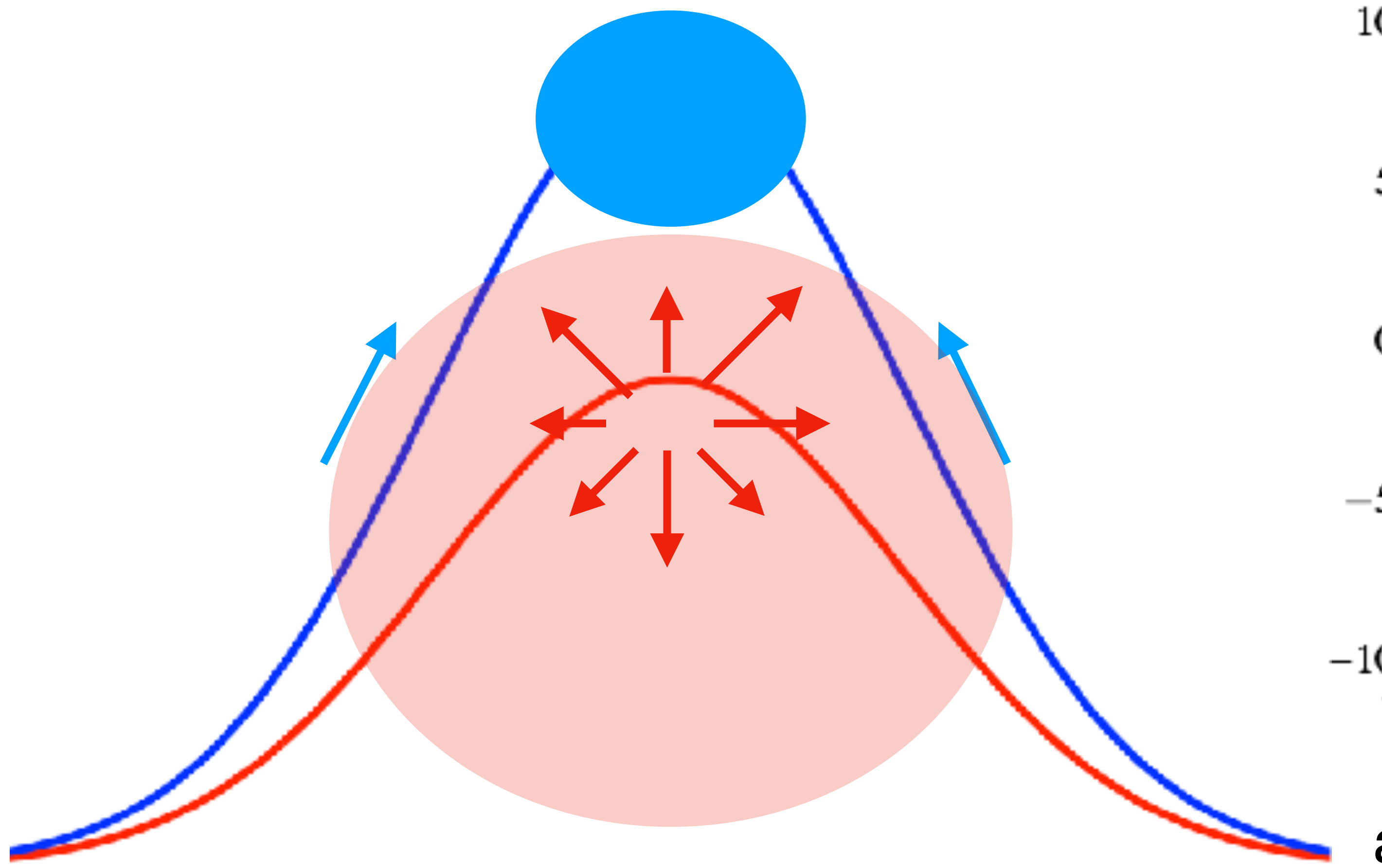


Girichidis et al. 2024

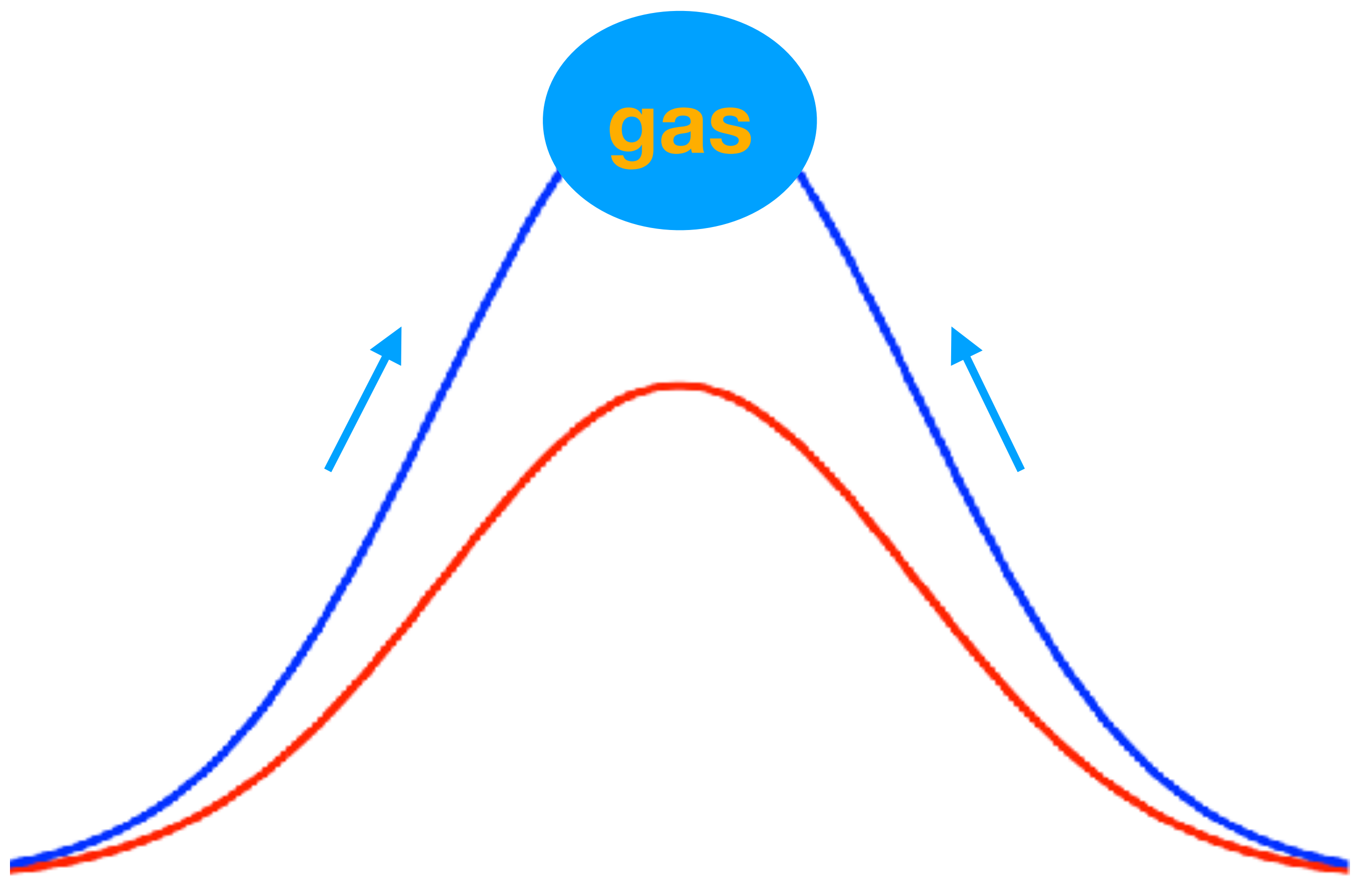
CR-driven dynamo

isotropic vs. anisotropic diffusion

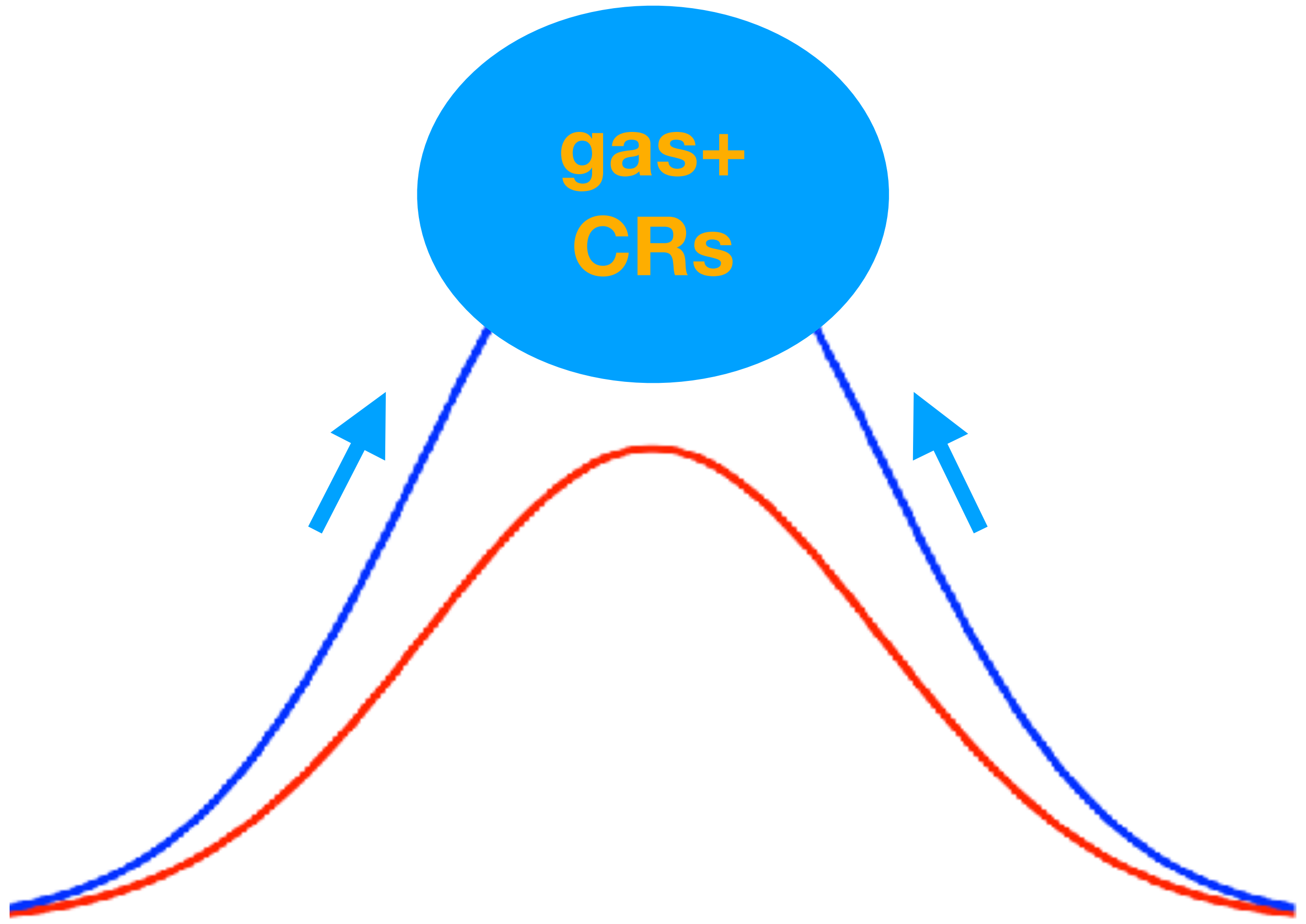
- compare
  - isotropic diffusion
  - anisotropic diffusion along field lines
- impact on B-field strength
  enhance Parker loops (Parker 1992)
- stronger α effect
  (Hanasz & Lesch 2000, Lesch & Hanasz 2003)



thermal Parker loop

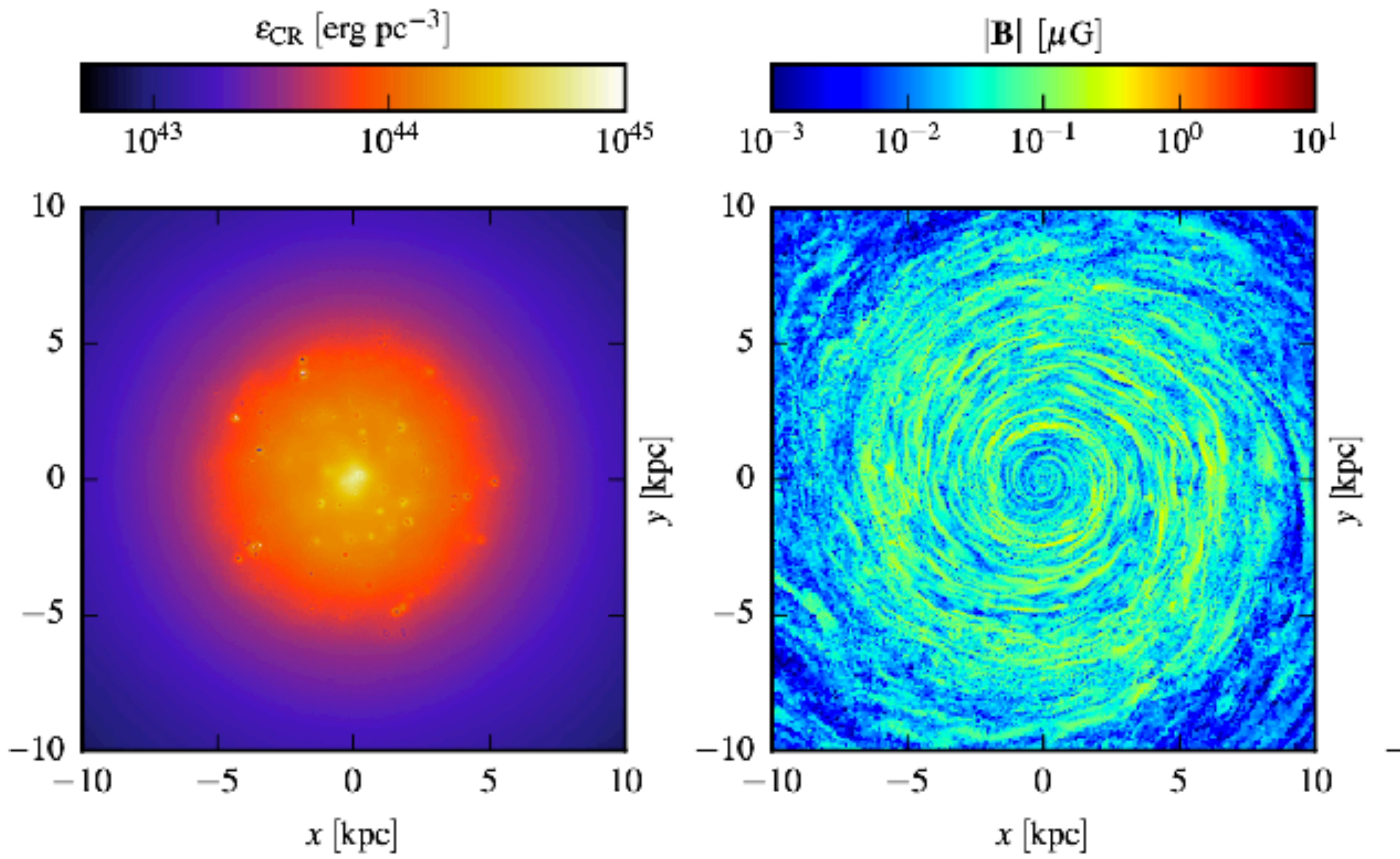


CR enhanced Parker loop

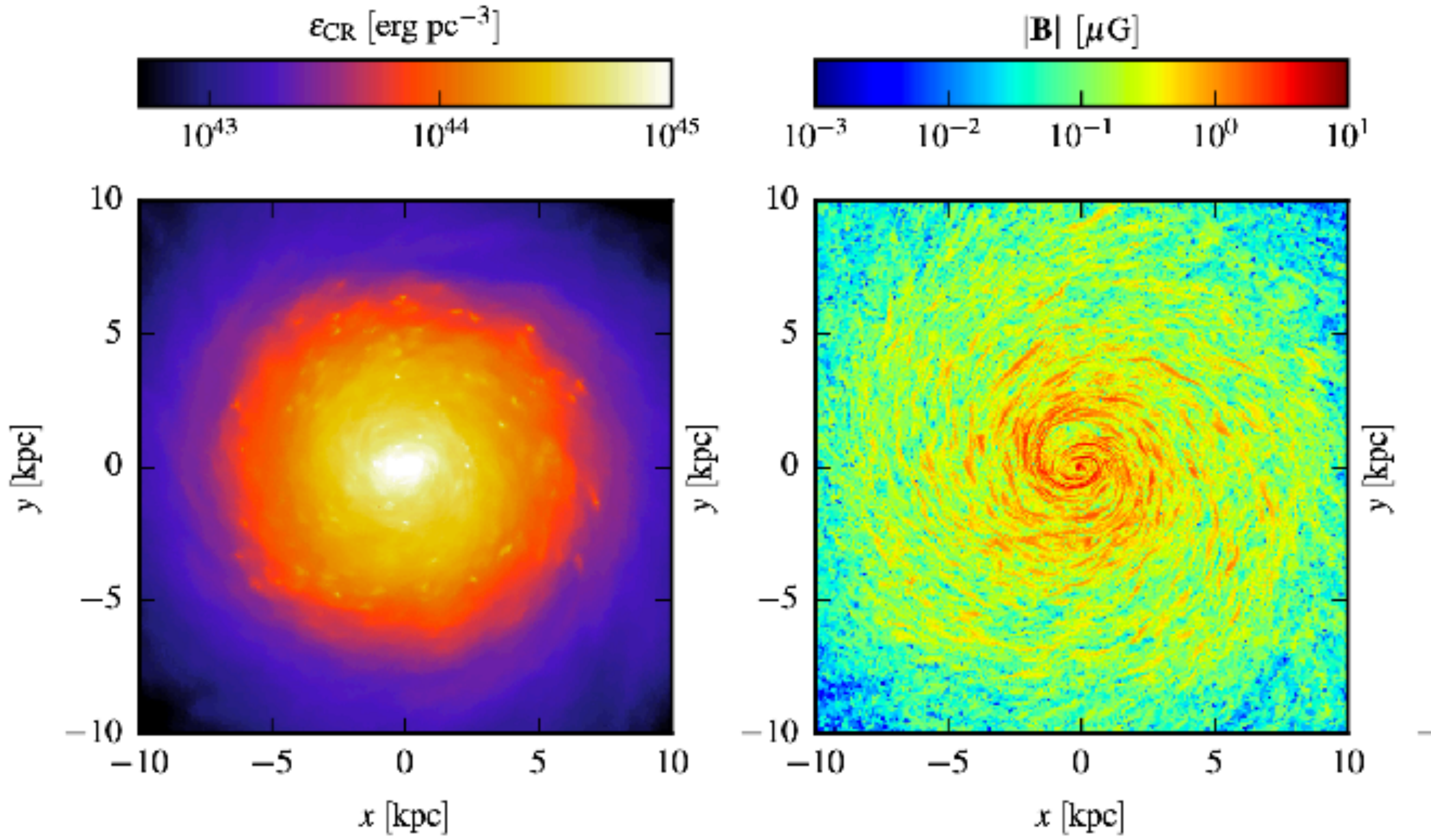


Pakmor et al. 2016

isotropic diffusion



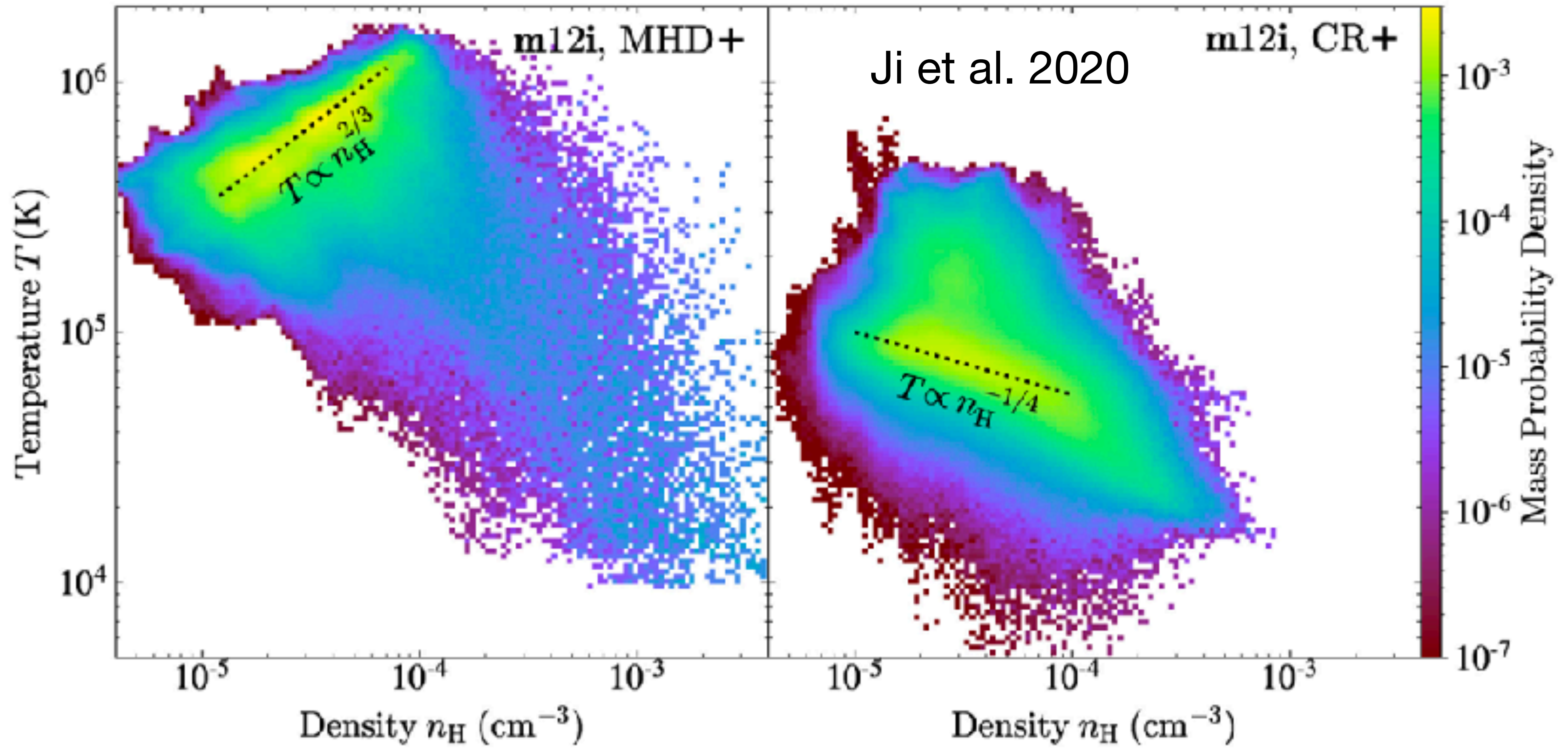
anisotropic diffusion along B

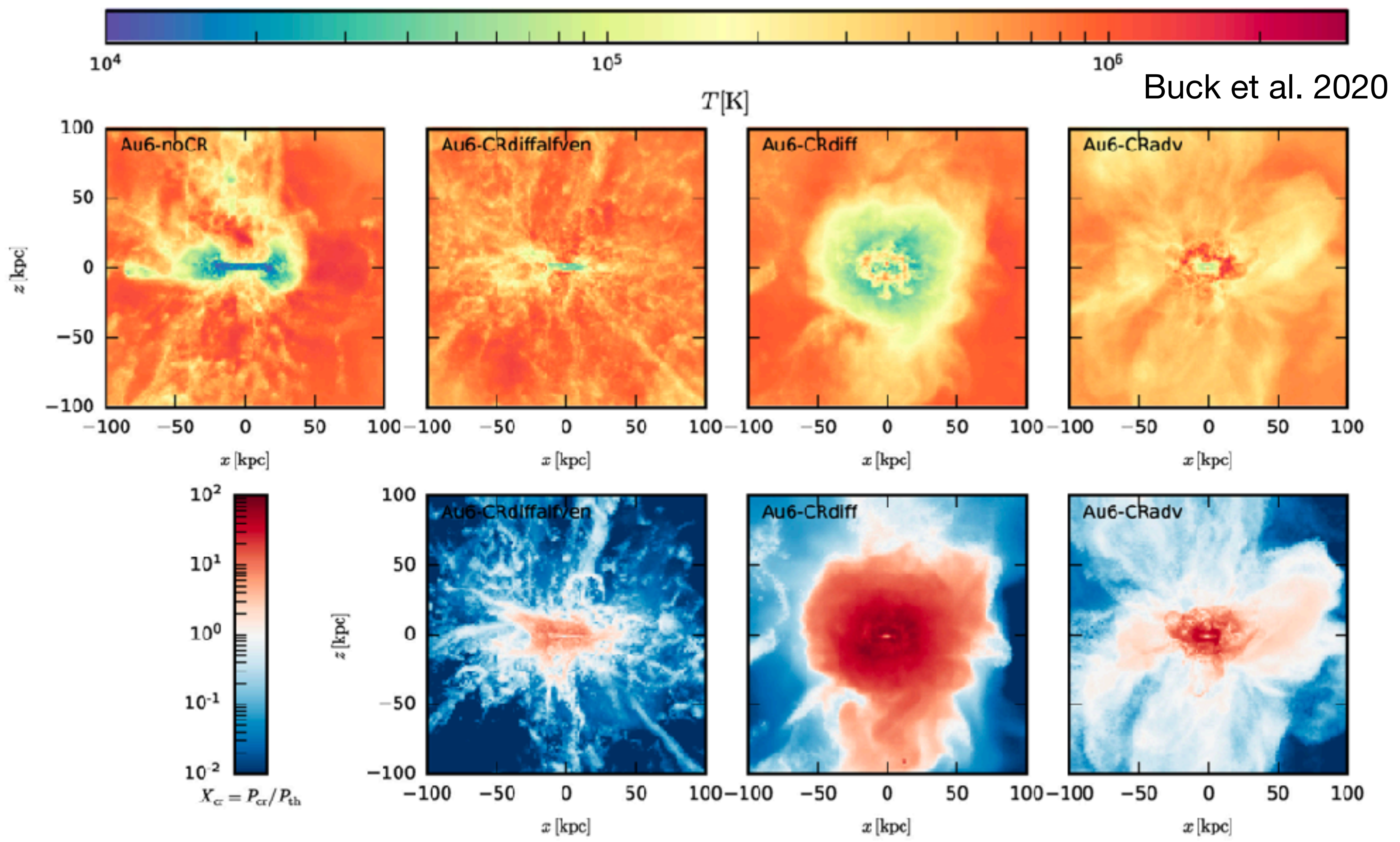


Cosmological zoom-ins

turbulent CGM, accretion

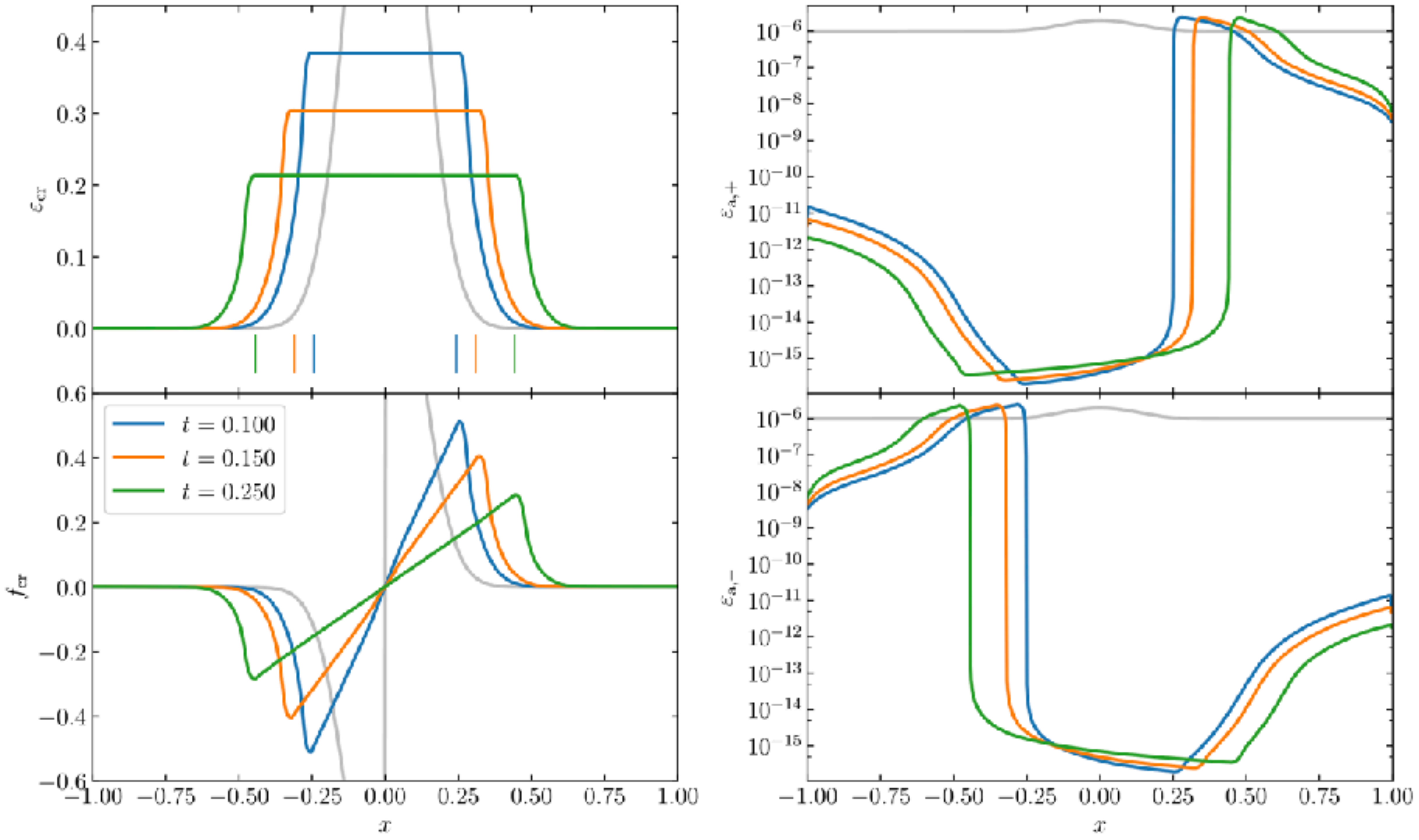
- include realistic environment around galaxies (turb. & accretion)
- effect of CRs extends >100kpc into halo (T, $X_{\rm cr} = P_{\rm cr}/P_{\rm therm}$)
- details of CR transport and losses matter

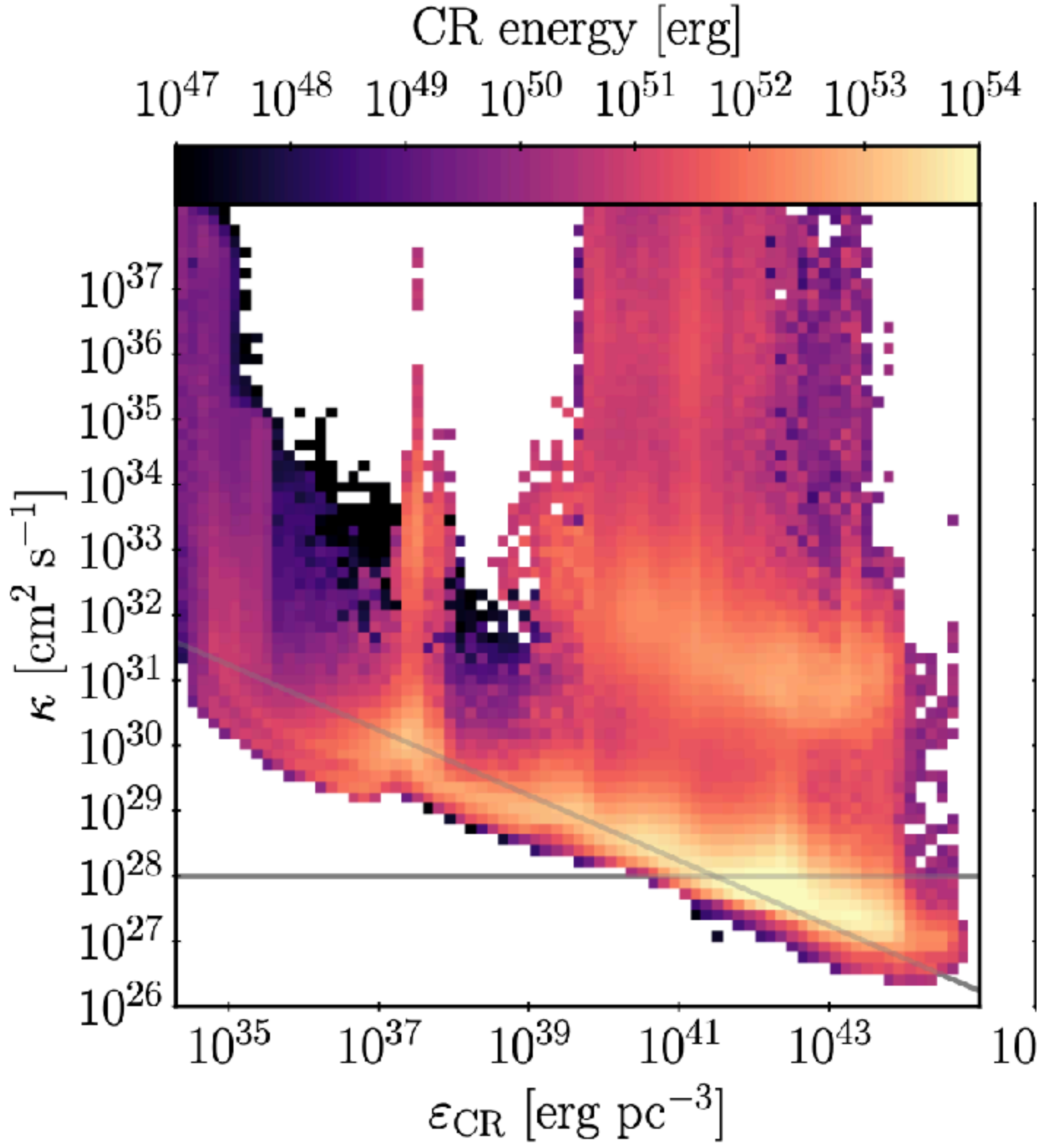




More accurate coupling CR ⇔ gas+B

- new approach in fluid approximation
- Thomas+ 2019,2021,2022:
  - follow CR energy AND energy in magnetic waves
  - averaged over p, given fixed spectrum



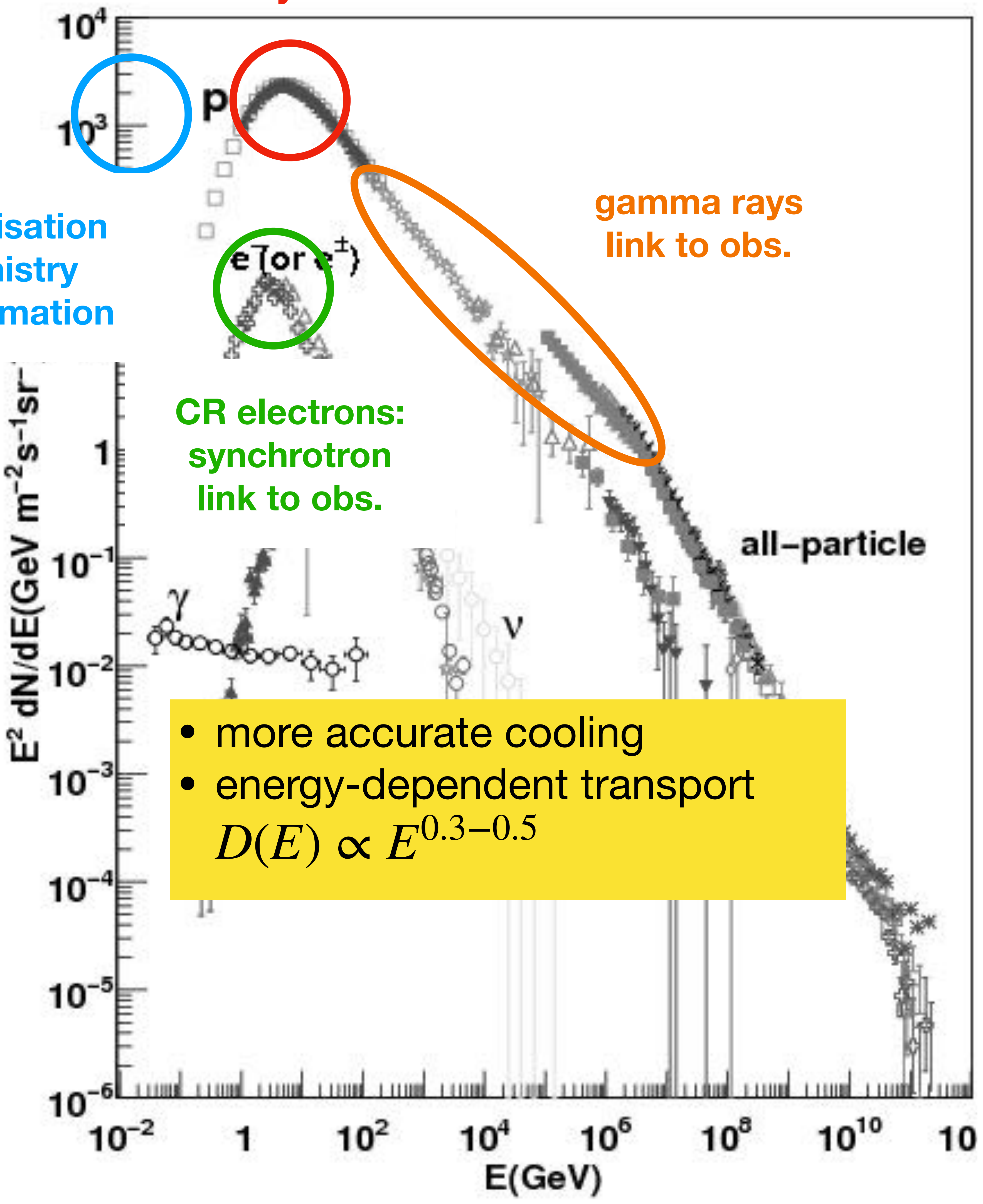


Thomas et al. 2022

Extension to spectral code

main dynamics

CR ionisation
chemistry
star formation

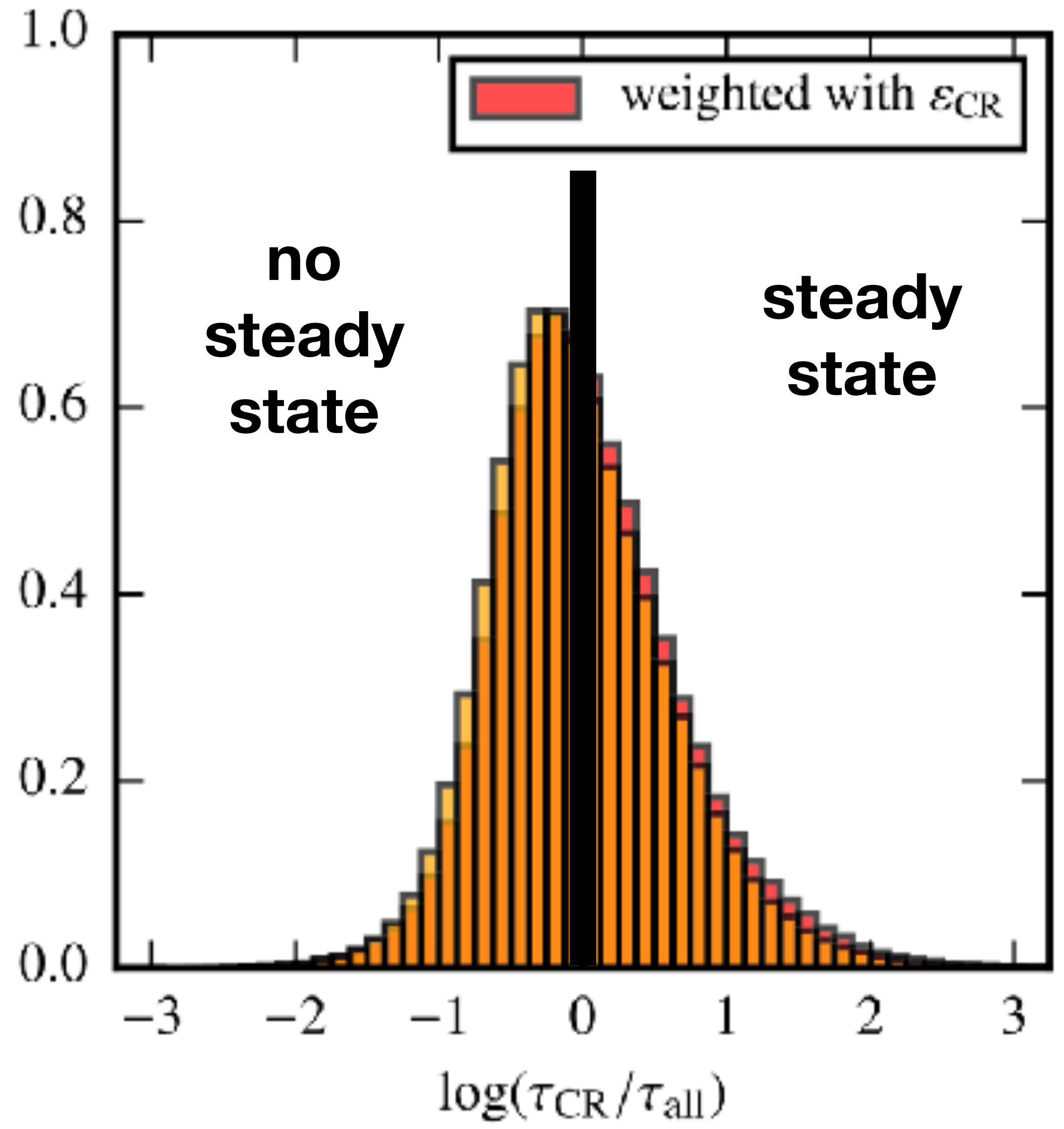


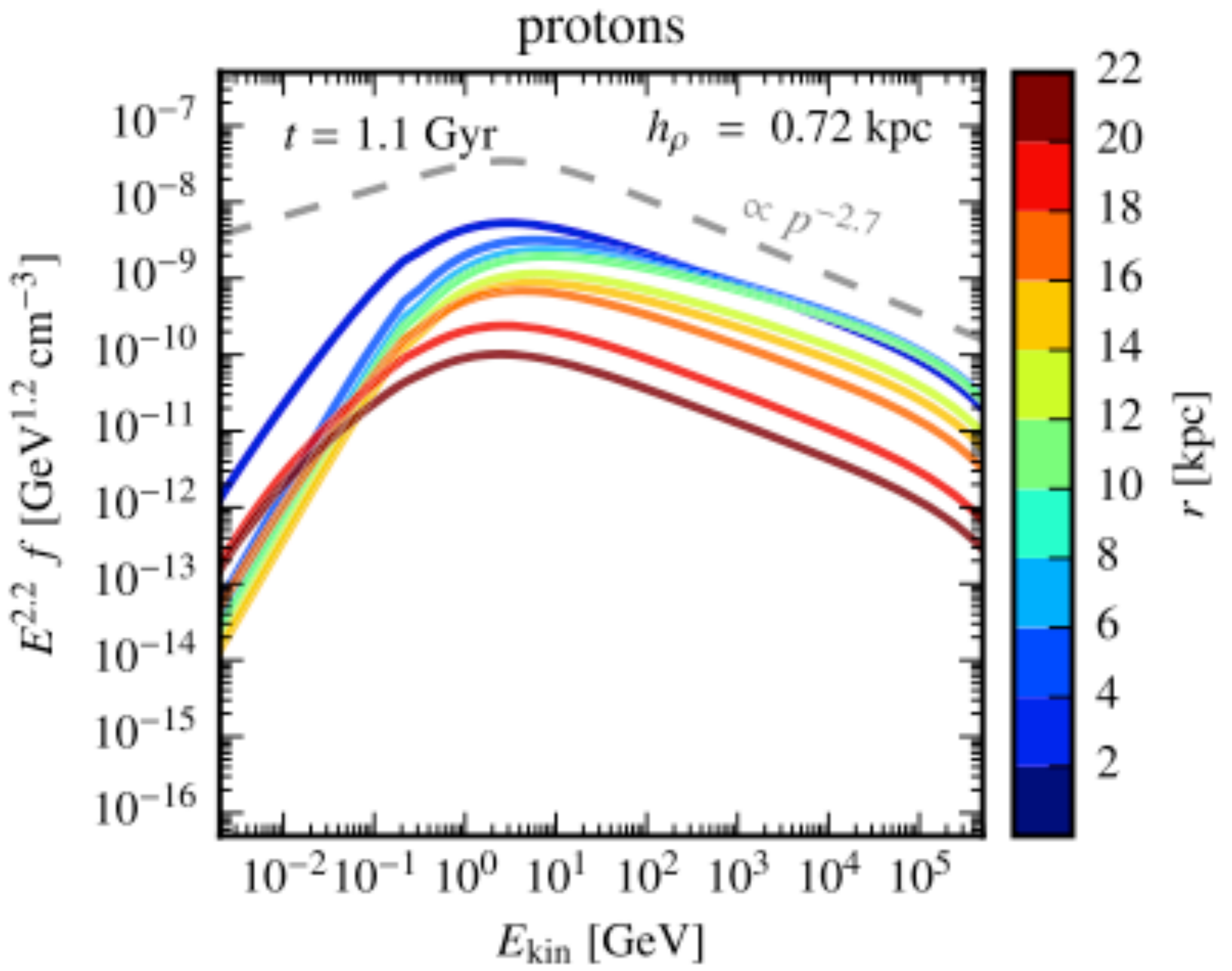
gamma rays
link to obs.

CR electrons:
synchrotron
link to obs.

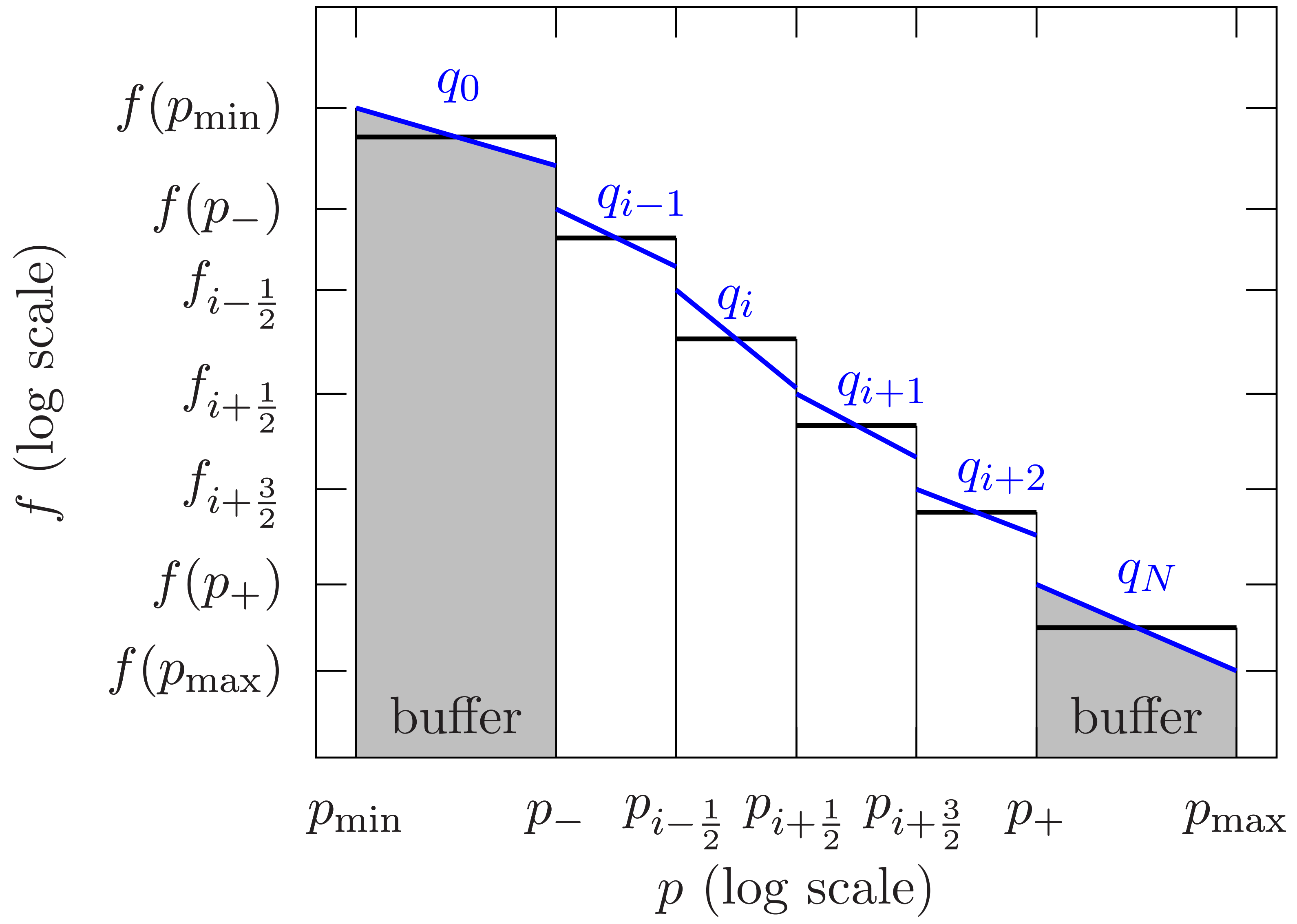
- more accurate cooling
- energy-dependent transport $D(E) \propto E^{0.3-0.5}$

Werhahn et al. 2021





Girichidis et al. 2020



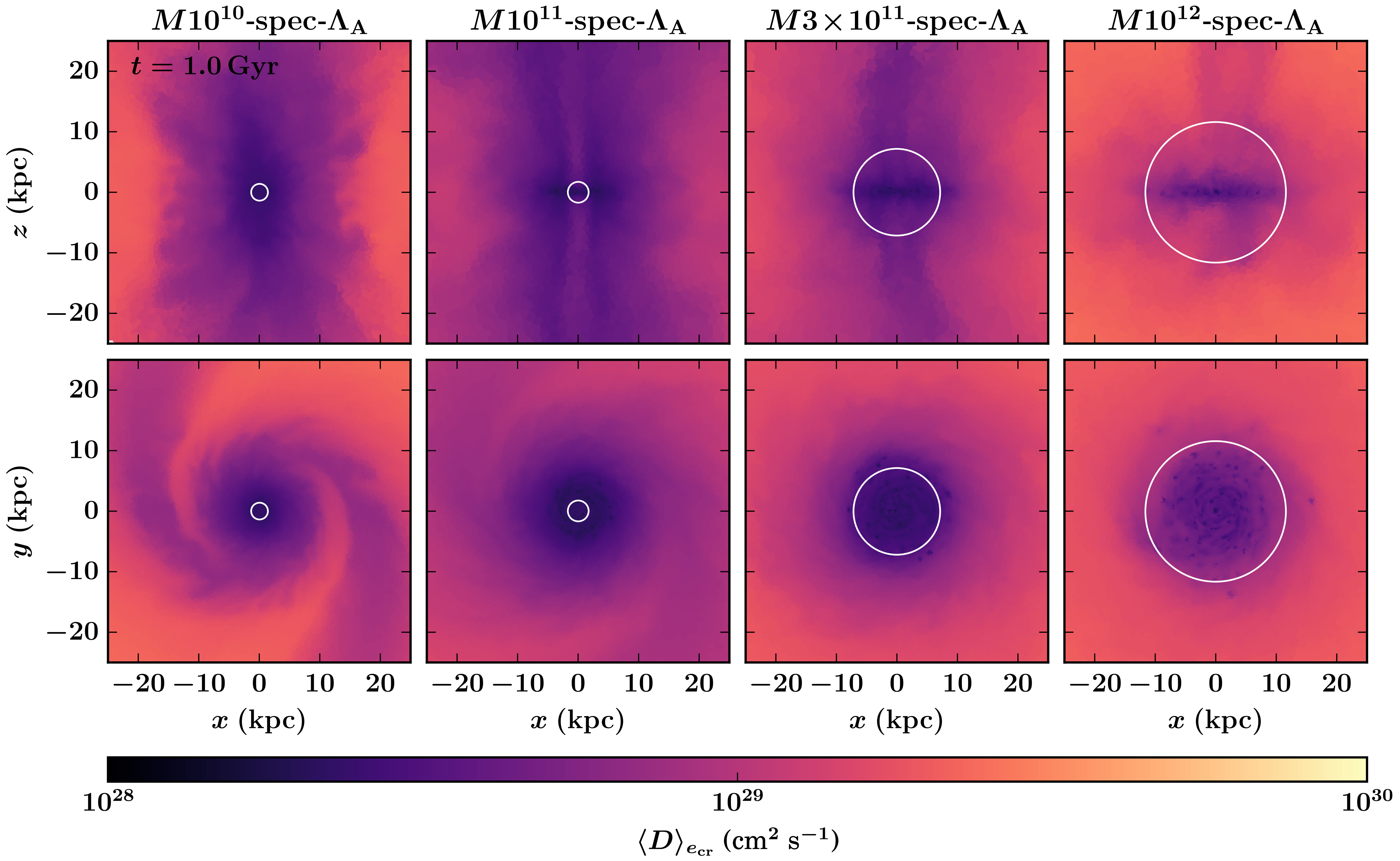
- often no steady state
- spectral variations important

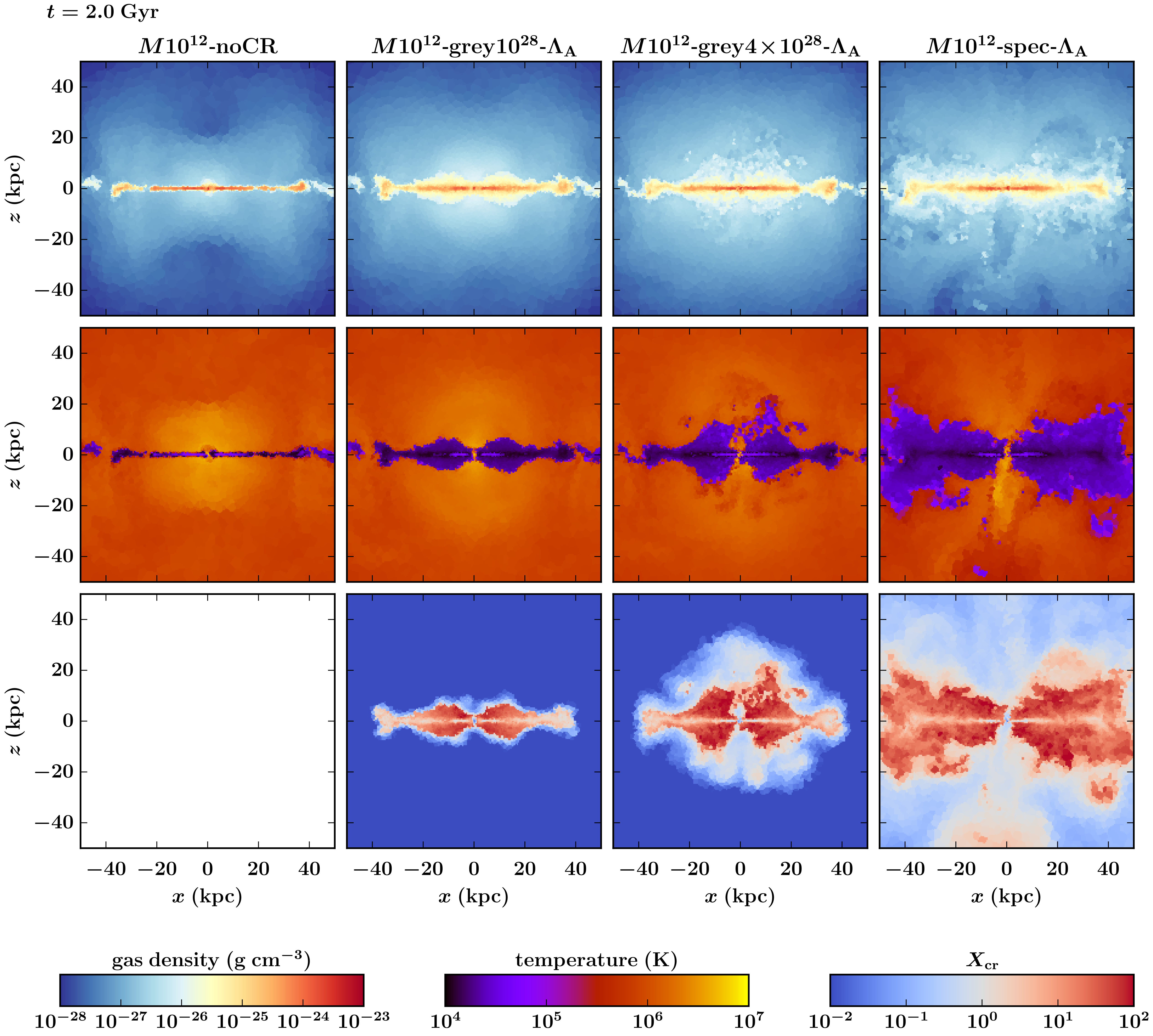
Spectrally resolved CRs

temperature and CR content

Girichidis et al. 2022, 2024

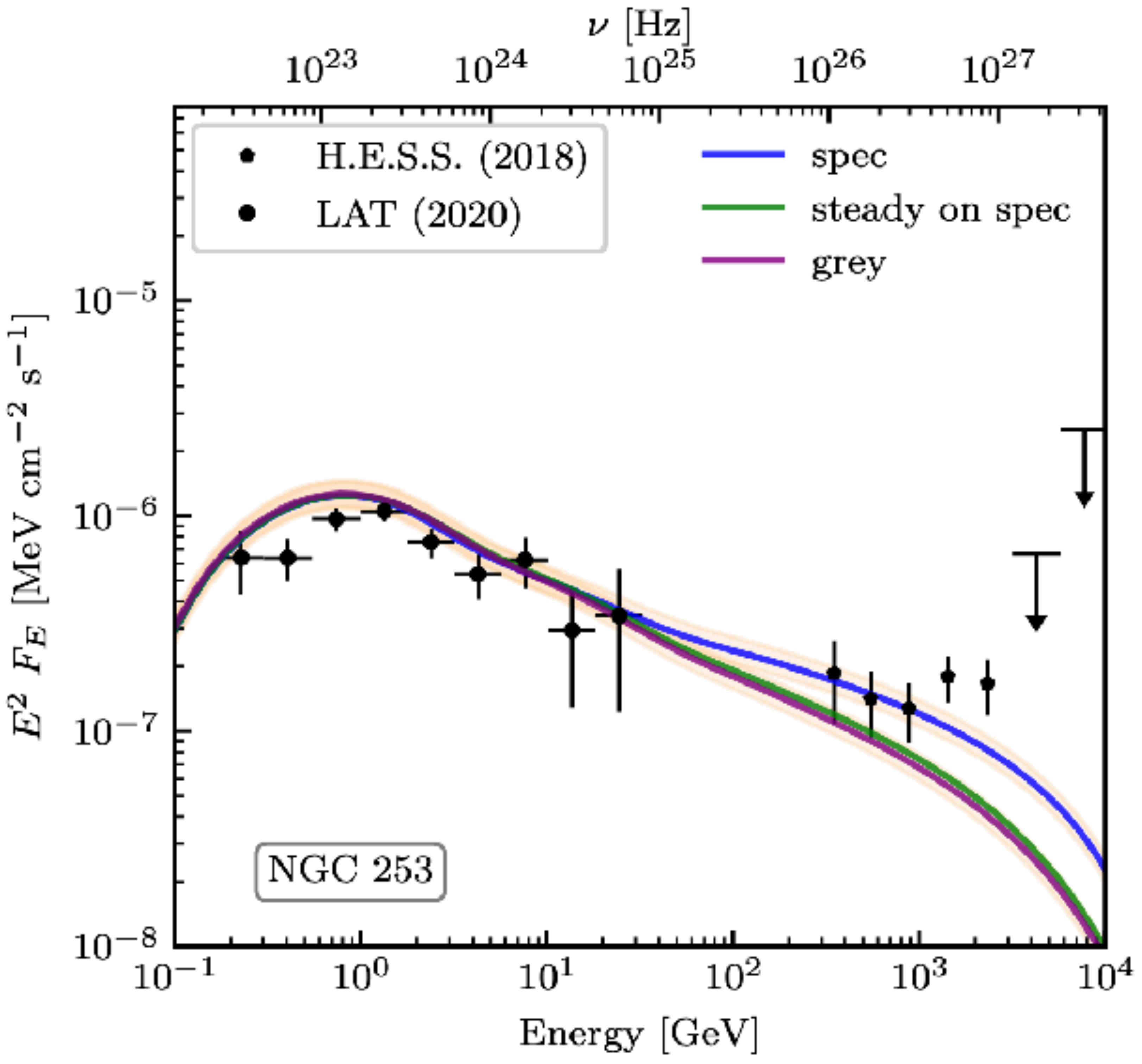
- high-E CRs escape faster
  variations in spectral shape and $D_\mathrm{eff} = \langle D(p) \rangle_\mathrm{e}$
- larger region of cold CGM
  impact on gal. fountain
- larger region with CR dominated pressure

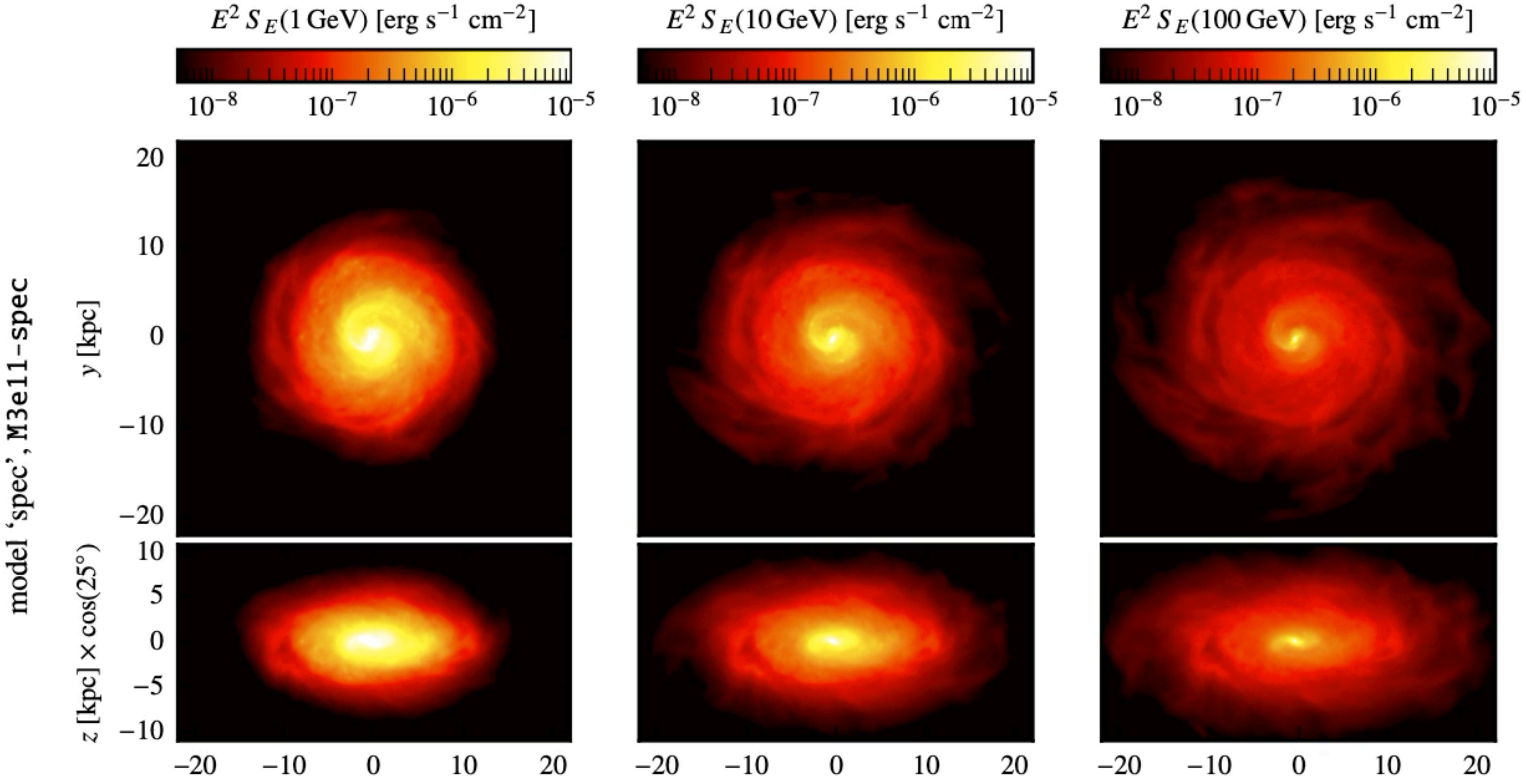




Connection to gamma rays

- Steady state vs. full spectrum (Werhahn+ 2021abc, 2023)





Werhahn et al. 2023

- spectral model: better fit to spectra

strong differences between energy ranges

Summary

- Magnetic fields need efficient dynamo conditions!
    - high resolution, resolved vortices (or subgrid model)
- CRs cool less efficiently than thermal gas and $e_{\rm cr} \sim e_{\rm kin} \sim e_{\rm therm} \sim e_{\rm mag}$
- CR drive outflows from galaxy and substantially change CGM
- big construction sites in CR physics
    - transport details (diffusion/streaming, transport speed)
    - details of the spectrum (high-E $\Leftrightarrow$ γ-rays, low-E $\Leftrightarrow$ ionisation rate)